ANALYSIS OF FILTRATION ABILITIES OF GEOTEXTILE LEACHATE FILTERS IN SOLID WASTE LANDFILLS

A Thesis

Submitted to the faculty

of

Rose-Hulman Institute of Technology

by

Reinhard Wolfram Koenig

In Partial Fulfillment of the

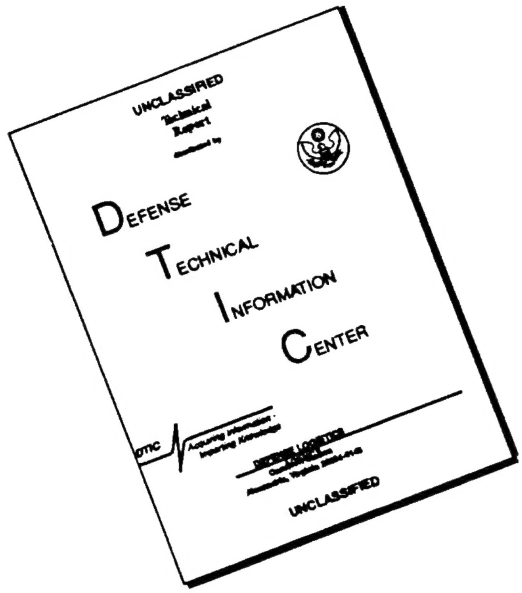
Requirements for the Degree

of

Master of Science in Environmental Engineering

May 1996

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

ABSTRACT

Koenig, Reinhard Wolfram. M.S., Rose-Hulman Institute of Technology, Analysis of Filtration Abilities of Geotextile Leachate Filters in Solid Waste Landfills. Major Professor: Dr. Martin J. Thomas.

Subtitle D of the Resource Conservation and Recovery Act promulgated strict design, construction, and operation standards for Solid Waste Landfills. Most notably it requires the use of an effective leachate collection system to ensure that leachate does not leak into the surrounding environment and groundwater.

An integral part of the leachate collection system is the use of a filter media which separates the solid waste from the collection system and ensures that the leachate system does not become clogged. Currently two major design strategies have been used to fulfill this function. They are to use either a sand media or a geotextile. The trend today is for the use of a geotextile. This has the advantages of being easier to install, more cost effective, and more dependable in many cases.

Research in the past has focused on the clogging of these geotextiles which serve as a filter for landfill leachate. Although it can be predicted with some certainty when the geotextile will clog, it is not known if geotextiles will provide removal of any leachate contaminants.

In the course of this research, the filtering ability of four separate geotextiles were investigated. One new design using a geocomposite was also tested to see if it could enhance the performance of the filtering system. Geosynthetics ability to remove chemical oxygen demand, biochemical oxygen demand, total suspended solids, zinc, and iron was examined. Verification of the clogging potential of these geosynthetics was also conducted and compared to past research. Both high and low concentration synthetic (mixed in the labaratory) leachates were used to compare the differences in the geotextiles.

It was found that all geotextiles tested removed statistically significant amounts of the TSS and COD load. Removals were found to be proportional to pollutant load. BOD, iron, and zinc were removed in statistically significant quantities only on a case by case basis during this research. Clogging potential was verified with past studies.

The geocomposite that was tested maintained generally higher permittivities while not removing as many of the contaminants. Site specific considerations must always be used when choosing a geosynthetic for solid waste landfill leachate filtration.

To my wife Sandy, and parents Ronald and Kriemhild Koenig

ACKNOWLEDGMENTS

I would like to thank Dr. Martin J. Thomas for guiding me through this research process and for introducing me to the environmental engineering field. I would also like to thank the entire Rose-Hulman family for making my wife and me feel at home and making the past three years both enjoyable and professionally rewarding. I'd like to thank my wife, Sandy, for her constant support through this and the many challenges Army life brings. Lastly, I'd like to thank the United States Army for allowing me to pursue this challenge.

TABLE OF CONTENTS

page

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 - INTRODUCTION

1.1 Background

The advent of modern society has brought on numerous changes. Many of these changes have brought us great convenience, enhanced our quality of life, and prolonged our lives. There has also been a cost. We live in a world that changes rapidly and many of these changes have had a negative impact on our environment. Our world today must deal with such environmental issues as air pollution, radiation contamination, the greenhouse effect, groundwater contamination, and many others.

There are two ways to negate the effects of an environmental problem. First we can change the habits of society in order to stop the environmental problem, or secondly, we can apply a technology based solution to the problem to mitigate the environmental effects of our actions. An example of the first strategy would be in order to reduce air pollution, we could simply stop driving our cars. An example of the second strategy would be to add pollution control devices to our automobiles in order to make them more "environmentally friendly."

A large environmental problem we face today deals with how we discard our solid wastes. It is estimated that each individual in the United States is responsible for generating approximately 4 pounds of solid waste per day (1:450). When this is considered in the larger context of a nation of 260 million people, this is an enormous problem (1:455). There are several ways of managing these wastes once our society

accumulates them. A general listing in a solid waste planning statute prioritizes strategies in order of preference as reduction, reuse, recycling, and composting over incineration and landfilling (2: not numbered). It is extremely unlikely that our society will ever achieve a state where it produces no solid waste. It is also unlikely that the strategies of reduction, recycle, reuse, and composting will totally eliminate the need for landfilling and incineration. Incineration reduces the volume of solid waste but ashes still must be disposed. The best we can hope for, especially in the short term, is to make sure that our landfilling practices minimize the impact on the environment while being economically acceptable.

Today there are approximately 227,000 municipal solid waste landfill facilities in the United States. This does not include the approximately 1,500 facilities that accept hazardous wastes as defined by Subtitle C under the Resource Conservation and Recovery Act (RCRA)(3:26). In 1991, the Environmental Protection Agency (EPA) issued strict guidance for the design and operation of municipal solid waste landfills under Subtitle D of RCRA. EPA mandated many new design features which have made the old neighborhood dump obsolete. Solid waste landfills are now complex systems which must be well planned, properly constructed, well maintained, and closely monitored even after closure.

The following research focuses on one of the relatively new design aspects of the modern solid waste landfill. Current Subtitle D regulations state that the solid waste landfill must have an adequate leachate collection system (LCS) (4:374). It is necessary to have a filter, whether a geotextile, geogrid, or soil, that separates the

products in the landfill from the LCS (5:1792). There are several products that are classified as geotextiles that are currently being used for this purpose. The purpose of this research is to determine the effectiveness of these geotextiles in filtering contaminants from leachate and verify clogging results from past research.

1.2 Geotextiles Used for Leachate Filtration

One of the primary concerns in employing a geotextile for use as a filter in a solid waste landfill is that the filter itself will clog and prevent leachate from reaching the LCS. Dr. Robert Koerner conducted an extensive study at the Geosynthetic Research Institute (GRI) at Drexel University to predict and define excessive clogging (6:1). In the study, he varied flow volumes, used different leachates and geotextile products, to look at the time for clogging. Major findings of this research include (6:1-8):

1. That under continuous flow of landfill leachate, a gradually decreasing flow rate will occur for all types of filters and flow will eventually reach an equilibrium value.

2. The equilibrium value of flow rate will vary according to the type of filter, the type of leachate, and the hydraulic gradient.

3. The equilibrium flow rate for any given filter system must be compared with the design required flow rate to ultimately assess the adequacy of the filter design.

4. Four different types of geotextiles were tested over a period of six months. The geotextiles retained their original flow rates in the following order: Lightweight needled non woven (38% of flow retained), heavyweight needled non woven (34%), woven monofilament (32%), and non woven heat bonded fabric (10%).

5. That leachates with higher Total Suspended Solids (TSS) loads as well as higher Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD) concentrations, tend to clog more. Although this was to be expected, the results did not show a direct correlation of clogging to concentrations in the leachate.

The results of Koerner's research is used to predict the clogging of the filter. They do not help predict the amounts of various contaminants that are removed by the filter. At no time during the research was the leachate tested after filtration, and it remains unknown what is actually being taken out by the filtration process. Koerner, Koerner, and Martin provided guidance for the design of the geotextile filter above the leachate collection system (5:1792). The Koerner research helps the designer predict clogging of the filter. One of the conclusions of this study was that it is important for the designer to use site specific data and testing when choosing the ultimate design.

As stated before, the research done by Koerner did not address whether contaminants are removed by a geotextile leachate collection filter system. Desharnis conducted research into the use of geotextiles as storm water filters. He tested geotextiles ability to filter BOD, TSS, metals, and other contaminants. In his research he found that only TSS was reduced significantly (7). Desharnis research, although very useful, does not answer the question of filtration of leachate from solid waste landfills because the concentration of contaminants in landfill leachate is several orders of magnitude higher than stormwater.

A literature review, private communications with Dr. Robert Koerner the Director of the GRI at Drexel University and Dr. David Daniel of the University of Texas at Austin, and communications with several industry representatives revealed no studies dealing with contaminant fate in geotextile filters in leachate collection systems (8,9,10,11).

1.3 Objective of the Thesis

This research is designed to determine several contaminant fate characteristics of geotextiles used in leachate collection systems. The objective of this research is to determine if there is a statistically significant change in the concentration of various contaminants in leachate as it passes through the geotextile filter. In the course of this research, the permittivity of the samples will also be tested to see if the same changes in clogging occur as found by Koerner in the Drexel University study. This will

require that the permittivity of the filter be tested over a ninety day volume of leachate flow. Two synthetic representative leachates will be used to evaluate contaminant fate characteristics and determine clogging potential of several geotextile filters and a geocomposite filter. Lastly, this research will propose the use of a geocomposite with a high permeability as an alternate design to see if it might be more effective in the filtration process.

This research will lead to:

1. A better understanding of the contaminant removal processes of geotextile filters and how geotextiles affect the quality of leachate.

2. A better understanding of the clogging mechanisms in geotextiles. Knowing the amount of removal from the leachate, particularly the organic chemicals and metals will help us better understand why and when the geotextile will clog. Most of the work to date has dealt with suspended solids.

3. Better predictions of the conditions under which geotextiles clog.

4. An increase in the use of these products. An increase in overall knowledge of the geotextile as a filter for solid waste landfill leachate may make them more attractive to landfill designers and operators which will lead to an increase in the available space of the landfill and ultimately reduce cost.

5. The ability of manufactures to design better products for use as leachate collection system filters.

6. Better prediction of the lifetime of the filters based on how various contaminants interact with the geotextile.

1.4 Landfill Impacts

Two components of a modern community are the need for water and the need to dispose of solid wastes. These two needs may not always be compatible. Probably the best way to solve this conflict is to ensure that we engineer our solid waste landfills so as to minimize the possibility of contaminants leaving the landfill.

Landfilling of solid waste poses a risk people by threatening the soil and groundwater supplies around the landfill itself. Metals and hazardous chemicals that leach from a landfill can make groundwater unusable. Approximately 50% of all fresh water supplies in America are pumped from the ground (1:197). Landfills near lakes and streams can leach into nearby groundwater bodies where they can enter the ecosystem and cause problems for humans and animals alike. Contamination of these valuable sources can have negative economic as well as health impacts on our society.

Landfills use up scarce land area. Urban areas with high population densities must contend with either using valuable land or shipping long distances, both at high

costs. The cost of landfill construction is estimated to be one million dollars per acre (12).

1.5 Landfill Regulation

1.5.1 Common and Civil Law

Common Law refers to the body of case law principles that have been derived from precedent (i.e. previous legal decisions). Civil Law is the means of governing disputes between private parties. When a tort or grievance is brought under civil law, it can be brought as a nuisance, trespass, or negligence.

With regard to solid waste landfills, Civil Law has been used and still can be used to address grievances. For example, a landfill operator who causes contamination of groundwater that his neighbor uses for drinking water, can be sued. The suit may be based on a trespass, negligence, or nuisance (13).

1.5.2 Legislative History

1.5.2.1 The Resource Conservation and Recovery Act

In October of 1976, the Resource Conservation and Recovery Act (RCRA) was enacted. RCRA was the first piece of environmental legislation that regulated the

disposal of both hazardous and solid wastes. RCRA imposed several important mandates with regard to solid waste disposal:

1. That all open dumps were to be closed or upgraded to landfills by the mid-1980s.

2. That federal government agencies make maximum use of recycled materials.

1.5.2.2 Hazardous and Solid Waste Amendments

In 1984, Congress reauthorized RCRA, enacting the Hazardous and Solid Waste Amendments (HSWA) to RCRA. HSWA revised the original legislation, bringing more small quantity generators of hazardous waste under the regulation, banning the land disposal of certain items (e.g. free liquids, untreated hazardous solids), and establishing stricter design standards for landfills and surface impoundments (1:491).

Section 3004 of the legislation required the Environmental Protection Agency (EPA) to establish levels or methods of treatment which substantially reduce the likelihood of migration of hazardous contaminants from waste so that short-term and long-term threats to human health and the environment are mitigated (14:663). Congress established a timetable for the promulgation of regulations for the safe

treatment and disposal of wastes. Part of this requirement was that EPA establish minimum requirements for the design and operation of solid waste landfills. This is contained in Subtitle D of the Code of Federal Relation 40CFR258.

1.5.3 Regulations Pursuant to Federal Law

1.5.3.1 Subtitle D

On 11 September 1991, pursuant to the HSWA mandate, EPA promulgated regulations for the safe design, construction, and operation of solid waste landfills. The design requirements for solid waste landfills liners are contained in 40CFR258.40. Specific requirements for the design include (4:375):

1. That the system not allow the uppermost aquifer to exceed the stated concentration (Maximum Contaminant Level - MCL) for various substances such as arsenic, iron, lead, cadmium, zinc, and mercury.

2. That the system have a composite liner consisting of two components: the upper component consisting of a minimum 30-mil flexible membrane liner and the lower component consisting of at least two feet of compacted soil with a hydraulic conductivity of no more that $1x10^{-7}$ cm/sec.

3. That the Director can approve a plan for an alternate design that complies with the design criteria above.

The EPA also promulgated rules governing other aspects of the landfill including the use of leachate collection systems (LCS), groundwater monitoring wells, off-gas collection, and closure procedures. Subtitle D also required each state to submit a plan for regulating solid waste landfills within their borders. These plans are required to be at least as stringent as federal regulations.

1.5.3.2 State Regulation

The EPA was to issue rules for the design of solid waste landfills no later than 1988, however, final rules were not issued until 1991. By then, many states had already enacted rules for the safe disposal of waste. All but Utah, Alaska, and Hawaii required the use of at least a single clay liner system which acts as a soil barrier to slow groundwater movement (15:8). Several required various liner systems on a case by case basis, and many had mandated the use of synthetic liners which are thin barriers made of petroleum products which act as nearly impervious barriers. New York State for example already required the use of a combination of two synthetic and two clay liners which is also known as a double composite liner.

Indiana had regulations in place which were in compliance with RCRA before the enactment of Subtitle D. The Indiana Department of Environmental Management

(IDEM) enacted rules that go beyond Subtitle D in that they require at least a three foot compacted clay layer below the leachate collection system and that the synthetic liner be at least 60 mils thick which is double the thickness required by Subtitle D. Indiana also requires the operator to prove there is 10 feet of solid subgrade below the clay layer to prevent excessive settling and requires the use of an LCS filter (16).

1.5.3.3 Regulation of a Filter for the Leachate Collection System (LCS)

The EPA has not required the use of a filter system to ensure that LCS does not clog. EPA has, however, mandated that the leachate collection system operate so that no more than one foot of head develops on the synthetic barrier of the system.

It was recognized early in the design process of leachate collection systems that if the leachate entered the collection system with a high concentration of suspended solids and other substances, it may eventually become clogged. This clogging would make removal of leachate impossible and cause water to build up on the synthetic liner. An increase in pressure head on the liner will cause an increase in transport of water through the liner and into the environment.

As early as 1984, it was recognized that in order to prevent the LCS from failing, it was necessary to place some sort of a filter between the solid waste itself and the LCS. Work done by Ghassemi in 1985 (17:615) suggested using either a geotextile or sand separator to act as the filter in the system. Separating the lowest portion of the waste or initial operations layer of soil from the leachate collection

system is essential (18:46). IDEM requires that such filters be used. They require either a geotextile or a sand layer at least 18 inches thick with a permeability of $1x10^{-3}$ cm/sec or greater (16).

CHAPTER 2 - LANDFILL FUNCTION AND DESIGN

2.1 Purpose of Solid Waste Landfills

A solid waste landfill is a site that employs an engineering method of disposing of solid wastes on or in the land. It does so in a manner that minimizes environmental hazards by reducing the solid waste to the smallest practical volume and applying and compacting cover material at the end of each day (14:609). Solid waste itself takes many forms and has several names based on its character. The Institute for Solid Wastes has defined many terms for solid waste that are more specific of their nature. A listing of them is contained in Table 2.1.

The purpose of the solid waste landfill may be to dispose of all of these different types of wastes. In practice however this is highly unlikely. Solid waste landfills will generally be designed for and accept certain categories listed in Table 2.1. Because of space limitations, access to the waste cells, and local regulations, they will limit the kinds of wastes accepted. A landfill may not accept garbage, for example, because local regulations mandate composting of such items.

A hazardous waste is any substance that the EPA defines as dangerous because of its ignitability, corrosivity, reactivity, or toxicity. The EPA maintains a list of substances that meet this criteria and these substances are known as listed wastes. A characteristic waste is one that is not specifically listed but meets the criteria and therefore must be handled as a listed hazardous waste. The purpose of the

Table 2.1: Refuse by Kind and Composition

KIND	COMPOSITION
Garbage	Wastes from preparation, cooking and serving of food, market wastes, wastes from handling, storage, and sale of produce.
Rubbish	Combustible: paper, cartons, boxes, barrels, wood, excelsior, tree branches, yard trimmings, wood furniture, bedding, dunnage.
Ashes	Residue from fires used for cooking and heat and on site incineration.
Street Refuse	Sweepings, dirt, leaves, catch basin dirt, contents of litter receptacles.
Dead Animals	Cats, dogs, horses, cows, etc.
Vehicles	Unwanted cars and trucks left on public property.
Industrial Wastes	Food-processing wastes, boiler house cinders, lumber scraps, metal scraps, shavings.
Demolition Wastes	Lumber, pipes, brick, masonry, and other construction materials from razed buildings and other structures.
Construction	Scrap lumber, pipe, and other construction materials.
Special Wastes	Hazardous solids and liquids, explosives, pathological wastes and radioactive materials.
Sewage Residue	Solids from coarse screening and from grit chambers, septic tank sludge.

Source: (19)

characteristic waste definition is to ensure that dangerous substances are not mishandled just because they are not listed. Either listed or characteristic wastes must be disposed of by the method or methods described by Subtitle C. Standards in Subtitle C are more stringent than Subtitle D of RCRA and more costly, making it undesirable to dispose of a non-hazardous waste in a landfill that meets the requirements of Subtitle C.

There are many other items in Table 2.1 that probably would not go into a solid waste landfill. Used vehicles may be better disposed of in junk yards and there is most likely a used metal market for them. Many organic materials like leaves, grass clippings, and yard trimmings may be better suited and less costly to dispose of by composting. Recycling is also a much better option, when practical, for things like glass, paper, plastics, and cardboard.

2.2 Planning, Operation, and Design of Solid Waste Landfills

The solid waste landfill must be well planned, operated, and designed, in order to be environmentally safe and economically viable. The design is most important when choosing a geotextile filter for a leachate collection system but the other two aspects must also be understood.

2.2.1 Planning a Solid Waste Landfill

When planning a solid waste landfill, some of the many considerations that must be made include local zoning requirements, public opposition, proximity and access to the local population and infrastructure, and buffer areas (14:610). Not only does the planner need to consider landfill regulations, he must consider the social impacts of the site. The owner must plan for the volume of waste created over a specific time interval that he plans on accepting waste. Important environmental

considerations include local hydrology and climate, the water table level, proximity to wells, and wildlife habitat. Part of the planning process includes the owner showing the financial ability to conduct post-closure operations (mainly installing a cap) and providing for long term groundwater monitoring.

2.2.2 Operation of a Solid Waste Landfill

A solid waste landfill in operation is shown in Figure 2.1. The operator must choose appropriate equipment for operation of the site, choose safe and efficient routes of travel in and out of the site, control access for security purposes, and maintain the aesthetics. The site must coexist with the local community and the operator must ensure that operations are conducted in such a manner as to minimize public opposition. The operator must apply daily cover to the waste cells in order to minimize vector breeding areas and animal attraction, help control water movement, minimize fire hazards, and increase aesthetics (20:12-13). Lastly, the operation must be conducted in a manner that minimizes the requirements of post closure operations.

2.2.3 Design of a Solid Waste Landfill

One of the challenges that the designer must contend with is the many regulations that exist. Subtitle D contains the minimum standards as promulgated by the EPA. State, county, and local regulations for permitting and operation may be

Figure 2.1: Solid Waste Landfill in Operation, Victory Environmental Inc. Yaw Hill Facility, Terre Haute, Indiana (Note the tarp used as daily cover)

more stringent. A schematic of what are considered the minimum requirements for a landfill is shown in Figure 2.2. Some of the major components of the landfill include the cover or cap, the liner system, off-gas collection system (shown in Figure 2.3), groundwater monitoring wells, and the leachate treatment facility. The liner system is the focus of this research and is further discussed in the next section.

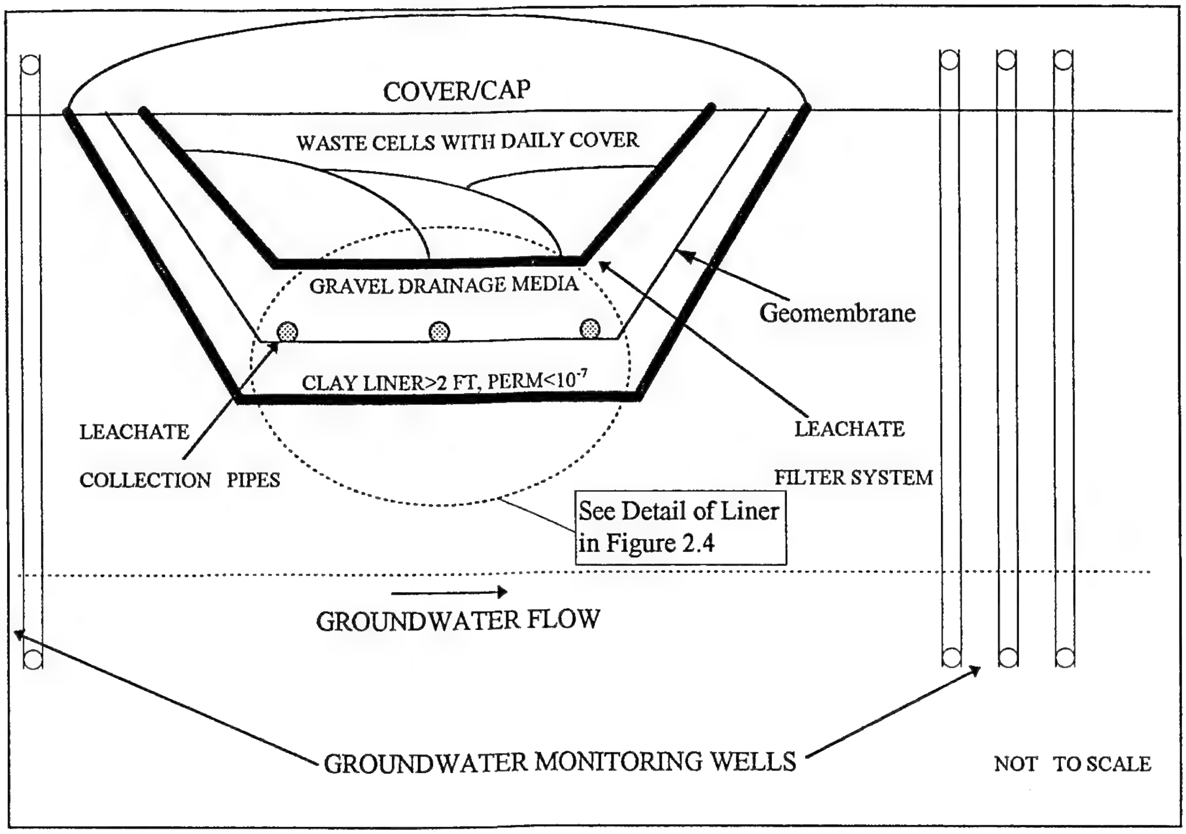


Figure 2.2 Municipal Solid Waste Landfill Design

Source: (14:549)

a.

b.

Figure 2.3: a. Leachate Collection Pipe Installed. b. Offgas Vent

2.2.4 Design of the Landfill Liner System

The purpose of the liner system is to envelope the solid waste and isolate it from the environment. When the liner fails, contamination of surrounding groundwater is likely. The liner system encompasses the portion of the landfill from the bottom of the waste down through to the undisturbed soil layer. Figure 2.4 shows the components of the liner system. It includes, from top to bottom, the filter system (the focus of this research), the leachate drainage media to include the leachate collection pipes, a geomembrane, a compacted clay layer, and the subgrade.

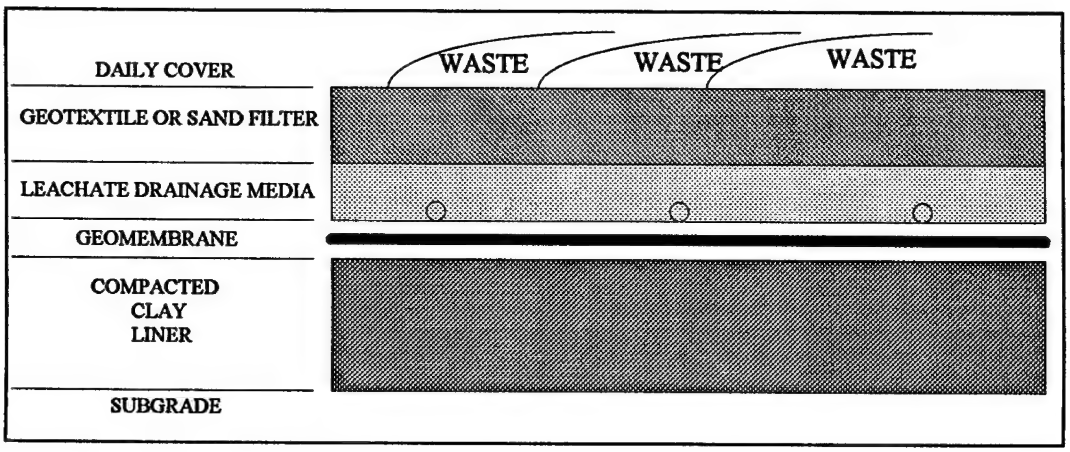


Figure 2.4: Components of the Solid Waste Landfill Liner

Source: (14:600)

2.2.4.1 Filter System

The purpose of the leachate collection filter is to act as a separation layer between the waste in the landfill and the leachate collection media. In order to do this effectively, it must allow adequate flow of the leachate into the underlying drainage layer so that a hydraulic head does not build up in the solid waste mass. Second, it must retain the particles above the filter layer so that the downstream drain itself does not become inundated with particles and become clogged. This applies to both the drainage media and the pipes in the LCS. Thirdly, it must itself not become clogged so that it will continue to pass the leachate along to the drainage layer. Balancing these three criteria is the heart of proper design of a leachate collection filter (5:1793-4). There are two common practices in leachate filtration. They are using either a geotextile or graded granular soil. Both are accepted practices.

2.2.4.1.1 Sand Filtration

Sand filtration takes advantage of the soils natural filtration abilities. Generally a soil with a permeability of greater than $1x10^{-3}$ cm/sec that is 18 inches thick can be emplaced to act as the filter. This practice is employed at Locksure Meadows Landfill, currently being constructed by Browning-Ferris Inc., in Evansville, Indiana. At this site, the filtration is accomplished by the use of various size aggregates, emplaced over the LCS (20). At the Yaw Hill Solid Waste Disposal Facility outside Terre Haute,

Indiana, 18 inches of sand is being used along with 18 inches of soil from the site to accomplish the filtration (12).

2.2.4.1.2 Geotextile Filtration

The current trend is away from soil filtration and towards geotextile use. Rumpke and Rumpke, Inc. which operates numerous solid waste landfills and is currently designing several throughout Indiana, Kentucky and Ohio, use them almost exclusively. This is primarily a cost consideration since the soil media for soil filtration is not readily available in the area and, hence, more expensive to emplace (21). There are other advantages. Because the geotextile is thinner, it provides more space for waste disposal. Geotextiles are also easier to engineer and provide good quality control because they can be selected to optimize filtration or flow. The Locksure site uses sand filtration is some areas, but in others uses a needle punched continuous filament non-woven geotextile (20).

2.2.4.2 Leachate Drainage System

The leachate drainage system will consist of a drainage media and perforated pipes to carry the leachate away. The installed pipe is shown in Figure 2.3 The engineer must design this system so that no more than one foot of head develops in the collection system. The drainage layer will consist of a well graded sand or other strata

with high permeability (greater than $1x10^{-3}cm/s$). Its purpose is to collect all leachate as it leaves the leachate filter and transfer it to the pipes for removal. A slight slope (1-3%) at the bottom of the drainage media causes the leachate to travel toward the center of the landfill. Here, at the lowest point in the drainage media, leachate collection pipes are laid perpendicular to the slope. These perforated pipes are usually made of polyvinyl chloride (PVC). The leachate travels through the media, the pipes, and then to a leachate holding tank to await final treatment. An example of a pumping station used to remove leachate from a holding tank is shown in Figure 2.5.

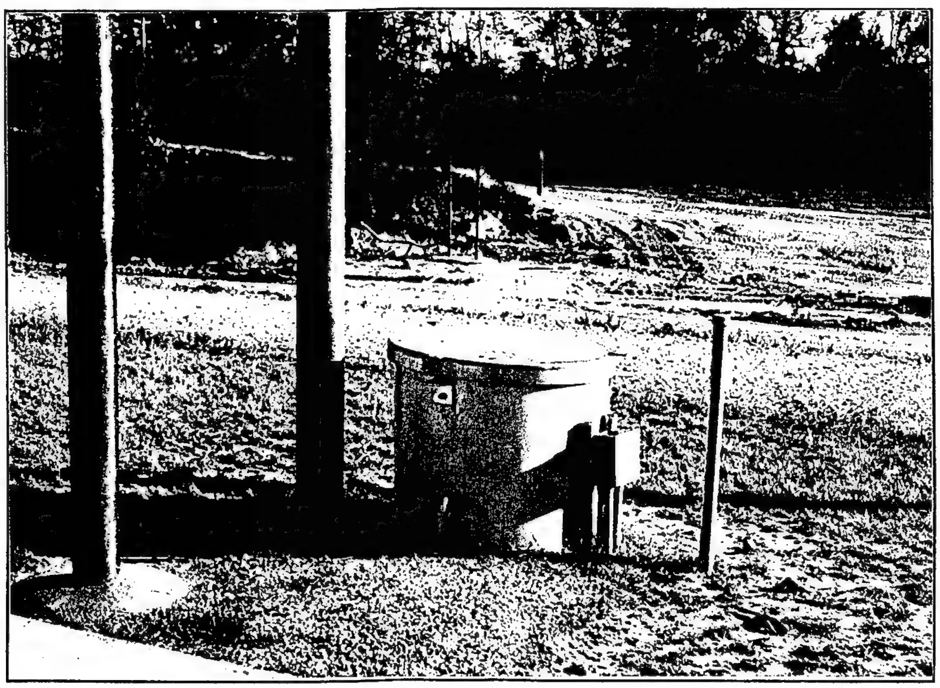


Figure 2.5: Leachate Pumping Station at Yaw Hill
Solid Waste Facility, Terre Haute, Indiana

2.2.4.3 Geomembrane

Between the drainage media and a layer of compacted clay is a geomembrane. A picture of a geomembrane being installed is shown in Figure 2.6. Its purpose is to ensure that a nearly impermeable barrier exists between the waste and the environment. By being impermeable, the geomembrane ensures that the landfill leachate travels no lower than the drainage media and that it does not escape the landfill. Subtitle D requires that it be at least 30 mils thick. A geomembrane must be resistant to the chemical properties of the waste as well as the local soil conditions. The action of a freeze/thaw cycle may be detrimental to the geomembrane and must be considered when choosing an actual product. The geomembrane is made of a high density polyethelene (HDPE) such as chlorinated polyethylene (CPE), chlorosulfonated polyethylene(CSPE) and others (18:48). Samples of the geomembrane may need to be tested for compatibility with the site specific wastes, as well as for shearing and seam strength. Membranes are available in strips up to 30 feet wide (22:28). This will require that field seams be installed in almost all cases.

2.2.4.4 Compacted Clay Layer

Below the membrane and above the subgrade is a clay barrier. This barrier acts as a back-up to the geomembrane in that it has very low permeability. Subtitle D requires that it be at least two feet thick with a permeability of $1x10^{-7}$ cm/s or less (4).

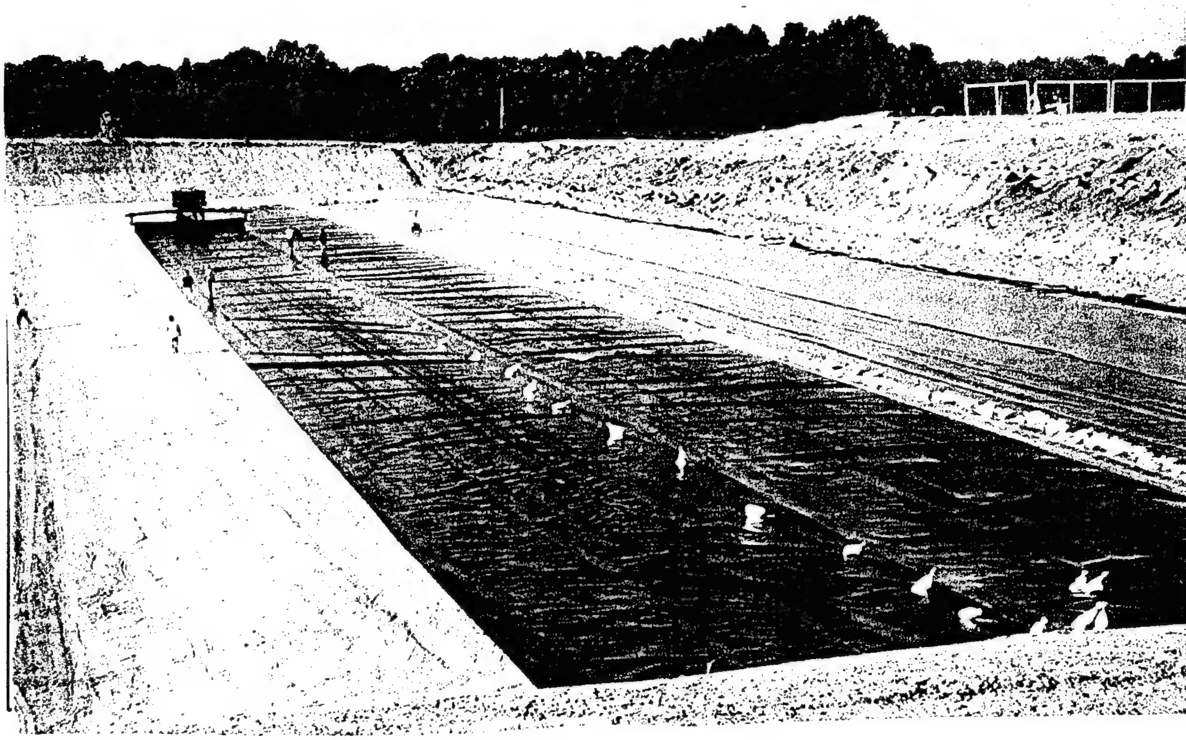


Figure 2.6: Geomembrane Being Installed at the Yaw Hill Solid Waste Disposal Facility, Terre Haute, Indiana

This layer is important because it is less prone to failure than the geomembrane above it because of the lack of seams. Quality control is very important when emplacing the clay to ensure that required minimum permittivities are met.

2.2.4.5 Subgrade

The last component of the liner will be the subgrade. This will serve as the foundation on which the entire system will rest. Site specific investigations are necessary to ensure that the subgrade will not cause failure of any of the liner components due to excessive settling. Indiana requires 10 feet of solid subgrade (16). If site investigations do not show 10 feet of solid subgrade, it must be emplaced and compacted.

CHAPTER 3 - SOLID WASTE LANDFILL LEACHATE

3.1 Description

A major concern inherent in landfill use is leachate contamination of ground water. Leachate is formed when liquids enters the landfill either as part of the solid waste being disposed or as rainwater infiltration. While the liquid is in the landfill, it will dissolve wastes. Eventually this leachate will travel through the landfill and into the groundwater if not intercepted by a LCS (23:3).

Ultimate composition of the leachate will vary from site to site, but it will have a large TSS, BOD and COD load, as well as various metals. When taken from a recently installed solid waste cell, the leachate will probably have a translucent light brown color. The odor is very disagreeable and nauseating (23:3). Leachate samples collected from an older solid waste fill are generally light brown to light yellow and the odor is not as offensive. The leachate will have viscosity similar to tap water.

3.2 Source

Although leachate may be present in waste when it is placed in a landfill, the primary source of the liquid for the leachate is rainwater infiltration. Although landfill covers and caps are designed to intercept rainwater and prevent it from entering the landfill, it is generally not possible to prevent all migration of water into the landfill.

This was recognized by the EPA when it promulgated its guidance for the design of landfill caps. EPA (40CFR258) regulations state that the cap should not allow more that five gallons per day per acre (46.8 liters per day per hectare) to seep into the landfill (24:64). This acknowledges that some water will infiltrate from the surface into the landfill and create the need for an LCS.

The amount of leachate generated by the landfill has been studied extensively. Demetracopoulos, Sehayek, and Edogan have developed a mathematical model for the generation and transport of solute contaminants through a solid waste landfill (25:849). The Environmental Protection Agency has developed and uses the Hydraulic Evaluation of Landfill Pollutants (HELP) Model to predict Leachate production. The Indiana Department of Environmental Management uses this model in all of its permitting decisions (16). Some of the main variables in determining the amount of leachate produced include the rainfall, the infiltration rate, characteristics of the waste, and thickness of the waste, as well as the dimensions and geometry of the site (5:1794). The amount of daily cover used can also be a factor in the final determination of the leachate production rate.

A study conducted by Ragle, Kissel, Ongerth, and Dewalle found that in the Western Washington landfill, the leachate production rate was anywhere from 506 to 4178 liters per hour per hectare (54.1 to 447 gpd/ha) (26:240). A survey of New York State landfills conducted by Phaneuf in 1993 found that landfills produced leachate at a range of 417 to 1542 liters per hour per hectare (44.6 to 164.9 gpd/ha) (27:20-28). Extensive research into leachate production rates has shown that no

landfill has been found to produce more than 5000 liters per hour per hectare of leachate. Note that the Ragle and Phaneuf studies are on landfills that have not been capped and are still operational allowing much more rainfall infiltration.

3.3 Composition

The study by Ragle, Kissel, Ongerth, and DeWalle (1995) was one of the most extensive conducted involving the composition of landfill leachatae from both new and old sections of an existing fill (26:238). The results of this study is shown in Table 3.1. They show very high concentrations of contaminants.

Table 3.1: Leachate Characteristics of an Old and New Cell in a Landfill near Seattle, WA

	Old Site(16years)(21.8ha)		New Site(3years)(41.3 ha)	
Parameter	Median	Range	Median	Range
Chemical Oxygen Demand (mg/l)	9100	1200-75,000	7050	220-21,600
Total Organic Carbon (mg/l)	2000	79-81,000	1500	31-6800
Total Dissolved Solids(mg/l)	5460	840-12,600	4730	858-10,120
Iron (mg/l)	350	140-600	200	90-680
Manganese (mg/l)	15	5-27	28	15-28
Flow (l/(hr*ha)	1094	506-3406	3409	295-4178

Source: (26:240)

Studies have been conducted on clogging of geotextiles by leachate and the treatment of leachate. These studies typically used actual leachate from solid waste landfills. The composition of these leachates is summarized in Table 3.2. BOD, COD, TSS, iron, and zinc were not the only contaminants measured in these studies. However, they were common to all (except as noted) and are important paramaters in predicting environmental degradation. A study conducted by EPA in 1980 on synthetic liners exposed to leachate, used a synthetic (laboratory mixed) leachate that fell within range of Table 3.2 (28:14).

Table 3.2: Composition of Leachate of Various Studies

Study/Source	pH	BOD_5 (mg/l)	COD (mg/l)	TSS (mg/l)	Iron (mg/l)	Zinc (mg/l)
(29:142)	6.0	10,000	18,000	500	20 - 1200	not reported
(30:315)	7.4	25,000	45,000	16,000	not reported	not reported
	6.5	2500	10,000	5000	not reported	not reported
(31:31)	5.95	3035	5028	204	102	17.6
	6.21	11,900	23,800	539	540	21.5
(32:257)	not reported	373	1167	274	41.4	.18
(33:28)	5.5	1500	not reported	3000	600	.6
(34:182)	6.25	2340	5400	not reported	400	.41

All of the parameters reported in Table 3.2 have a large range (e.g. the COD values range from 45,000 to 1167 mg/l). Qusim has reported that the wide range in contaminant concentrations is due to the wide range in age, composition, and depth of the waste, the composition of the landfill cap and daily cover, and rate of liquid infiltration for the different landfilles (29:129).

3.4 EPA Testing Requirements

In 1975, the EPA issued recommendations that leachate be tested for COD, pH, conductivity, and TSS (23:10). In 1991, the EPA required groundwater monitoring wells be installed at solid waste sites as part of the Subtitle D of RCRA. The monitoring program requires the testing of 45 organic chemicals and 15 heavy metals on a semi annual basis (15:8). Recently, the EPA has relaxed the testing requirements by allowing for two phases of testing. Phase I monitoring calls for at least semi-annual sampling of 24 inorganic parameters and certain volatile organic compounds. If any of these samples exceed maximum contaminant levels established by EPA, then Phase II monitoring is implemented, which requires that many more parameters be tested at 90 day intervals. If standards are still exceeded, then a corrective action program must be established (29:91).

CHAPTER 4 - GEOTEXTILE DESCRIPTION AND USES

4.1 Geotextiles in General

Geotextiles fall into the family of geosynthetics that includes geomembranes, geogrids, geopipes, and geonets. The American Society of Testing and Materials (ASTM) defines the geosynthetic as "a planar product manufactured from polymeric material used with soil, rock, earth, or other geotechnical engineering related material as an integral part of a man-made project, structure, or system (35:20)." They define the geotextile as "a permeable geosynthetic comprised solely of textiles (35:20)." The geotextile is really any geosynthetic that is manufactured for the purpose of allowing fluid to pass through while retaining the media behind it.

Geotextile use in civil engineering projects has greatly expanded in the past 25 years. In 1970, few geotextiles were available. Since then over 400 million square yards of the material have been used throughout the world. Total sales of geotextiles exceeded 390 million dollars in 1992 (36:7). This is part of the overall $1.3 billion geosynthetic market. Geotextiles first uses were in erosion control. Today they are used in the separation of dissimilar materials, reinforcement of weak soils, for filtration (of primary concern here), and in drainage. Their biggest uses are as asphalt overlays and for separation and stabilization of soils (36:34-38).

4.2 Filtration Mechanism in Geotextiles

The filtration mechanism of a geotextile is depicted in Figure 4.1. Geotextiles hold back soil particles in the same manner as a layer of aggregate. This is done by blocking large particles while allowing smaller particles and water to pass. Some form of energy differential must exist across the barrier in order for water to flow across the boundary. Once a flow has been initiated, a filter cake is created by the particles that are unable to pass through the geotextile. After the filter cake is established, it will begin to act as a filter itself. Clogging occurs when this filter cake becomes so dense that it effectively creates an impermeable boundary that water can no longer pass through. Koerner showed that in leachate collection filters, flow never completely stops. The rate of flow decreases a great deal (permeabilty reduced to as low as $1x10^{-6}$ cm/sec), but that the reduction stops and eventually reaches a constant, low value. He found that this final, constant flow rate occurs anywhere from 60 to 200 days after leachate flow is initiated (5:1792-1798).

4.3 Design Characteristics of Geotextiles

There are many properties of geotextiles that determine what specific product is best suited for a particular project. These properties can be categorized as the physical properties such as weight, strength, and ultraviolet resistance, and their engineering properties like the permeability, retention efficiency, and slurry flow rates.

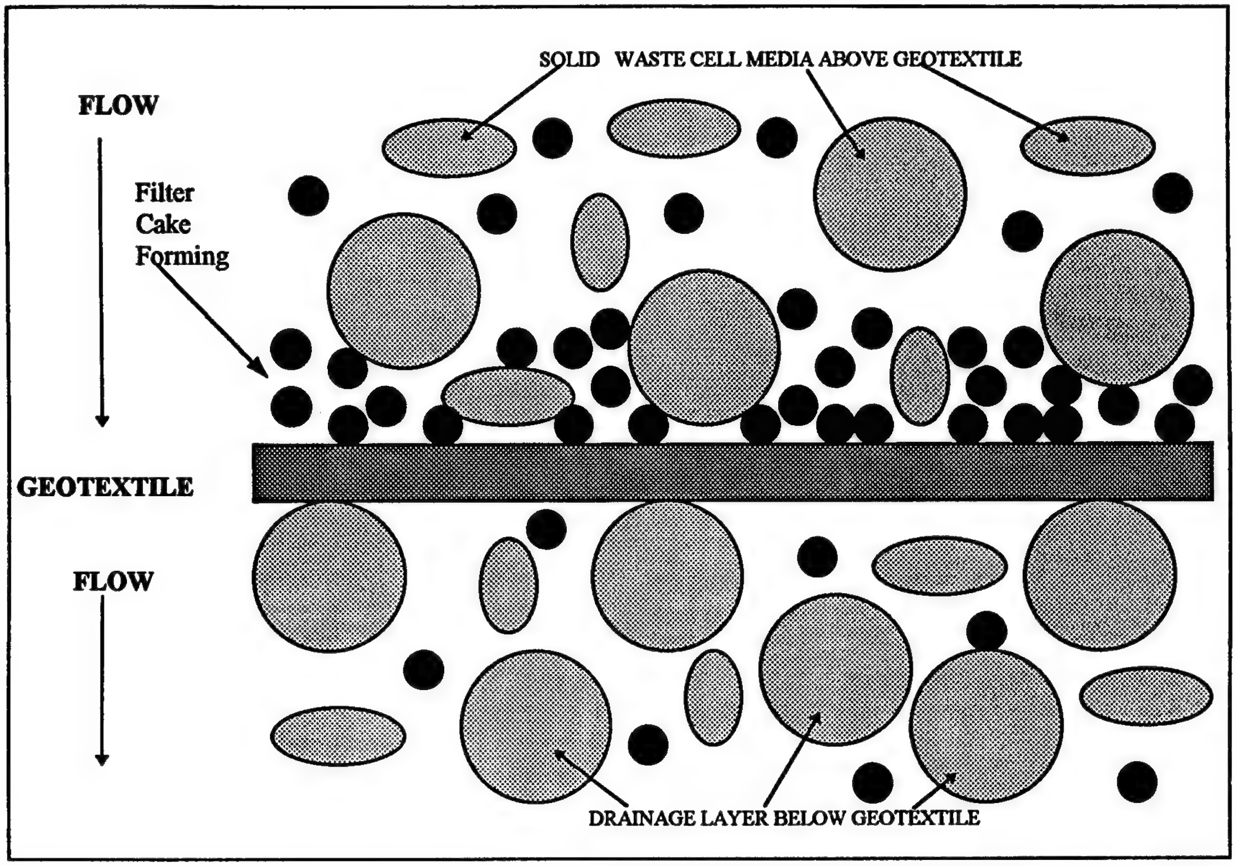


Figure 4.1 Mechanics Involved in a Geotextile Designed for Filtration

Source: (37:1.4)

Table 4.1 contains a listing of some of these properties, their units and a testing parameter. The weight is important in that IDEM does not allow the use of less than an 8 oz/yd^2 geotextiles for this filtration function (16).

Table 4.1 Design Properties of Geotextiles

Fabric Property	Units	Test Method
Grab Tensile Strength	lbs.	ASTM D1682
Grab Tensile Elongation	%	ASTM D1682
Burst Strength	psi	ASTM D751
Puncture Strength	lbs	ASTM D3787
Trapezoid Tear Strength	lbs	ASTM D1117
Apparent Opening Size	Sieve #	CW-02215
Water Permeability, k	cm/s	PTM no. 314
Abrasion Resistance	lbs	ASTM D1892
Slurry Flow Rate	gal/min/ft	VTM-51
Retention Efficiency	%	VTM-51
Percent Open Area	%	CW-02215
Sewn Seam Breaking Strength	lbs	ASTM D1682
Ultraviolet Resistance (retention)	lbs	ASTM D1682 after 500 hrs
Weight	oz/yd^2	none

Source: (36:69)

4.4 Classification of Geotextiles

With the large increase in use of geotextiles over the last 25 years, has come a great increase in the number and types of products available. Manufacturers have taken two different strategies in their efforts to market their products. They have either targeted their products for the large (commodity) market, or they have aimed for smaller (niche) specialized markets. In any case the products can be classified by the type of polymer used, the fiber used, and the style of the product (36:26)

The polymers used today are mainly polypropylene (83% of the products), polyester (14%), polyethylene (2%), and polyamide (1%) (39:26). All of theses specific polymers are man-made derivatives of various crude oils and natural gases. Table 4.2 contains a listing of the basic properties of polypropylene and polyester which are the two most common types of polymers used. From this information, it is difficult to predict which polymer is more effective as a leachate filter.

Table 4.2 Properties of Two most Common Polymers in Geotextiles

Property	Polyester	Polypropylene
Specific Gravity %	300	250
Absorbency of Water (gm/den)	0.04 - 0.08	0.01-0.1
Wet Breaking Tenacity %	3 - 8	4 - 8
Elongation at Breaking %	10 - 50	15 - 35
Resistance to Wear	Excellent	Good
Maximum Safe Temperature (^{O}F)	300	250
Resistance to Chemicals	Excellent	Excellent
Undergoes Hydrolysis	Undecided	No

Source: (37: 14.1-14.2)

These basic polymers are made into fibers by melting them and forcing them through a spinnet. The resulting fiber filaments are then hardened or solidified by a melting process. Final manufacturing of the yarn can result in the different types of fibers. They are (36:26-27):

1. Monofilament. Once the polymer exits the spinnet, it is stretched. This action reduces the fiber diameter and causes the molecules in the fibers to arrange themselves in a more orderly fashion.

2. Monofiliment. When two or more monofilaments are twisted together, the fiber is known as a multifilament.

3. Staple fibers. These are produced by continuous filaments of a specific diameter. They are bundled, crimped, and cut. Once cut into staples of one to four inches in length, they are twisted or spun into long yarns for subsequent fabric manufacturing.

4. Slit-films. These are very different in that the polymers are molded into a continuous sheet and then cut to the desired width.

5. Slit-film multifilament. Slit-film monofilaments can then be wrapped if desired to create a slit-film multifilament.

These types are used to manufacture the actual geotextile. Final products are usually divided into:

1. Wovens. Wovens are made on a conventional textile weaving machine into a number of different patterns and products. The pattern of the weave is determined by the sequence in which the wrap yarns are threaded into the weaving loom and the position of the warp harness for each filling pick (36:28). The most common type of weave is the plain weave, which is known as the once up and once down.

2. Nonwoven Nonwoven manufacturing generally follows the four steps of fiber preparation, web formation, web bonding, and post treatment. The fiber comes out of a spinnet and is placed in a random manner. It is then bonded by having the filaments adhere to each other by a thermal, chemical, or mechanical process. (36:32).

These three classifications (polymer type, fiber type, and woven vs. Nonwoven) characterize geotextiles. For example a geotextile may be known as a nonwoven needle punched polypropylene, a woven multifilament polyamid, a woven silt-film polyethylene, etc. Other parameters such as the apparent opening size, weight, and tensile strength will further describe the geotextile.

4.5 Geotextiles Tested in this Research

The use of geotextiles for leachate filtration is relatively new. As discussed in Chapter Two, there are several products. Based on research presented here and studies done to test the clogging ability of the soil in the past, the geotextiles in Table

4.3 were chosen for testing. They are shown in Figure 4.2. The table also contains some of their physical properties. They were chosen for testing for a wide variety of reasons. They include:

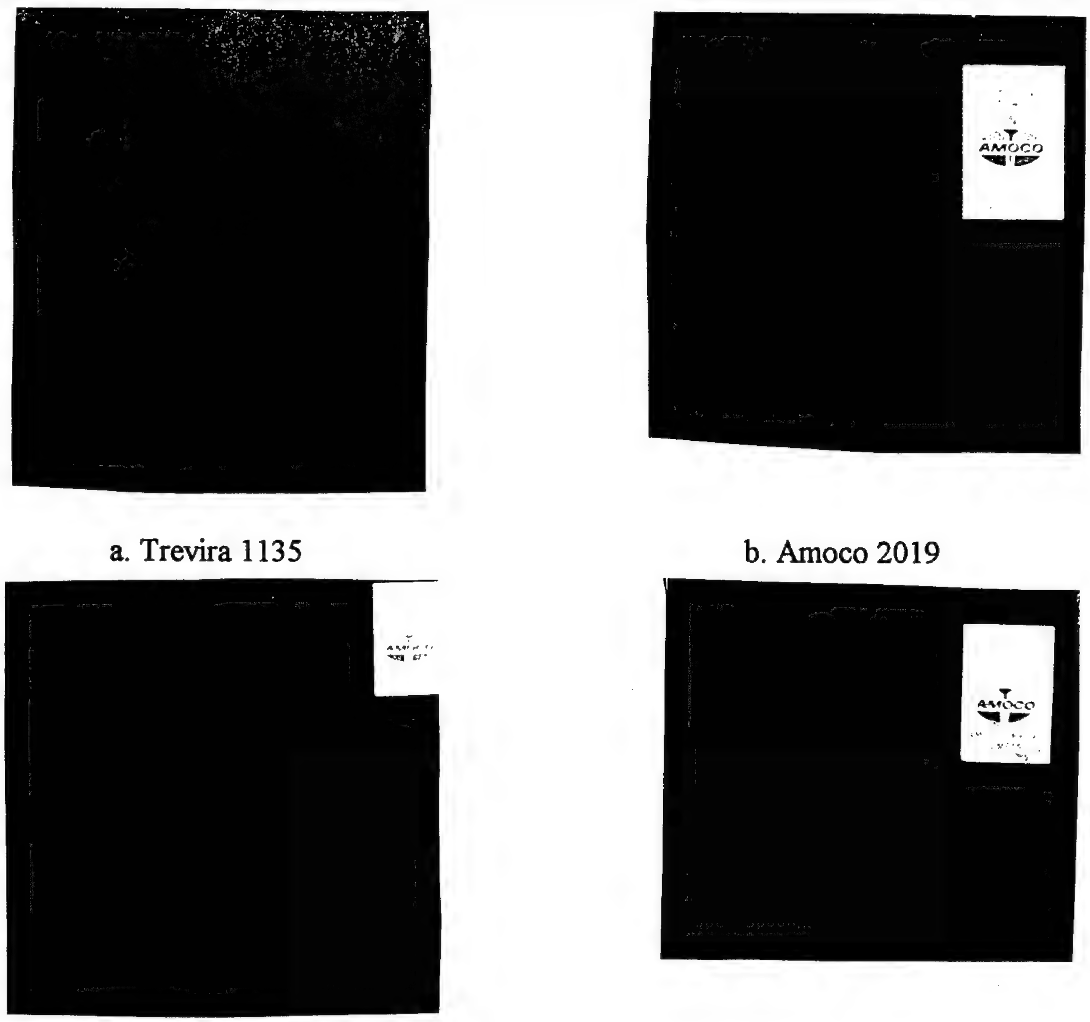
1. These four are representative of the wide range of products available. They are made of several different fabric types and have a range of permittivity values.

2. The Trevira 1135 was chosen because Desharnis (1995) found it to be effective in removing of suspended solids in his experiments.

3. The Amoco 2019 was chosen to test the abilities of a woven geotextile in this filtration function. It offers a significantly lower initial permittivity than the others. It will be used to determine if a geotextile with an initial low permittivity, retains a lower permittivity during testing.

4. The Amoco 4508 was chosen on the advice of Janice Duncan of Amoco Fabrics and Fibers Company. She stated that it is the most widely used product in the filtration of landfill leachate today. This product also has the characteristics of the geotextile used in the Koerner research, which has the most detailed analysis of permittivity changes (38,5).

5. The Amoco 4551 was chosen because it has a low permittivity for a nonwoven and low apparent opening size. It weighs less than the minimum requirements of IDEM and will , therefore provide information on the filtration and permittivity to the weight requirement.



a. Trevira 1135

b. Amoco 2019

c. Amoco 4508

d. Amoco 4551

Figure 4.2 Geotextiles Used in this Research

Table 4.3 Selected Geotextiles and their Physical Properties

Physical Property	Unit	Trevira 1135	Amoco 2019	Amoco 4508	Amoco 4551
Fabric Type	N/A	nonwoven	woven	nonwoven	nonwoven
Polymer Type	N/A	polyester	polypropylene	polypropylene	polypropylene
Fiber Type	N/A	continuous filament	filament	continuous filament	continuous filament
Bonding Process	N/A	needle punched	weaved	needle punched	needle punched
Weight	oz/ yd^2	10.5	8.5	8.0	6.6
Thickness	mils	140	N/A	115	N/A
Grab Strength	lbs	420-350	350-250	275-270	150
Grab Elongation	%	75-80	65	15	50
Trapezoid Tear Strength	lbs	140-125	65	140-210	65
Puncture Resistance	lbs	155	140	170	90
Mullen Burst Strength	psi	560	510	575	315
Permittivity	1/sec	1.6	0.04	1.8	1.6
Apparent Opening Size	U.S. Sieve Size	100-120	70	100-200	100

Source: (7,37)

CHAPTER 5 - NEW DESIGN FOR A SOLID WASTE LANDFILL FILTER

5.1 Geocomposites in General

The geosynthetics industry has developed a new set of products known as geocomposites. A geocomposite is any combination of two or more geosynthetics which takes advantage of the best features of each (36:58). This includes the use of geonets, geogrids, geotextiles, and geomembranes in any combination with each other. The products are bonded together through the use of chemical, thermal, or mechanical adhesion processes. They are generally manufactured for site specific purposes.

Landfills commonly use a geocomposite system to help reduce the thickness of the clay barrier under the geomembrane. It is common to see two geotextiles stitched together with a bentonite powder in between them. This forms a very low permeability barrier which can be useful as a backup liner below the geomembrane. When this is placed at the bottom of the clay barrier in a solid waste landfill, the state of Indiana reduces their required thickness of the clay liner from three feet, down to two feet (16).

An example of a geocomposite in a solid waste landfill is a solid polyvinyl chloride with a geotextile chemically bonded to one or both sides. The PVC acts as the impermeable barrier or geomembrane that is required by Subtitle D, while the geotextile on top will act as a partial substitute for the gravel drainage layer. Leachate

travels down through the waste through the gravel drainage layer and to the geotextile, and drains along the geomembrane liner where it is conveyed to the leachate collection pipes. This can effectively reduce the needed depth of the gravel drainage area which will increase the useable volume of the landfill. A geonet or geogrid may be used in a similar manner.

A geotextile or even a geogrid bonded to the bottom of the geomembrane will increase the friction between the geomembrane and the clay layer below it. This can be a critical need if there is a possibility of the geomembrane slipping on the clay layer (e.g. the side slopes of the landfill). By adding the geotextile to the bottom of the geomembrane, slippage can be minimized.

5.2 Geocomposite Proposed to Act as a More Effective Leachate Filter

A geocomposite may consist of two or more geotextiles bonded together and used for filtration. It is hoped that such a product can be found and that this product will offer better filtration capabilities while maintaining higher permittivities. Figure 5.1 depicts the action of the proposed geocomposite as leachate passed through it. The first layer, with large openings, filters out the large particles in the leachate. The second layer, with smaller openings, filters out smaller particles. This action is much the same as that in a dual media rapid sand filter only the depth of the media is greatly decreased.

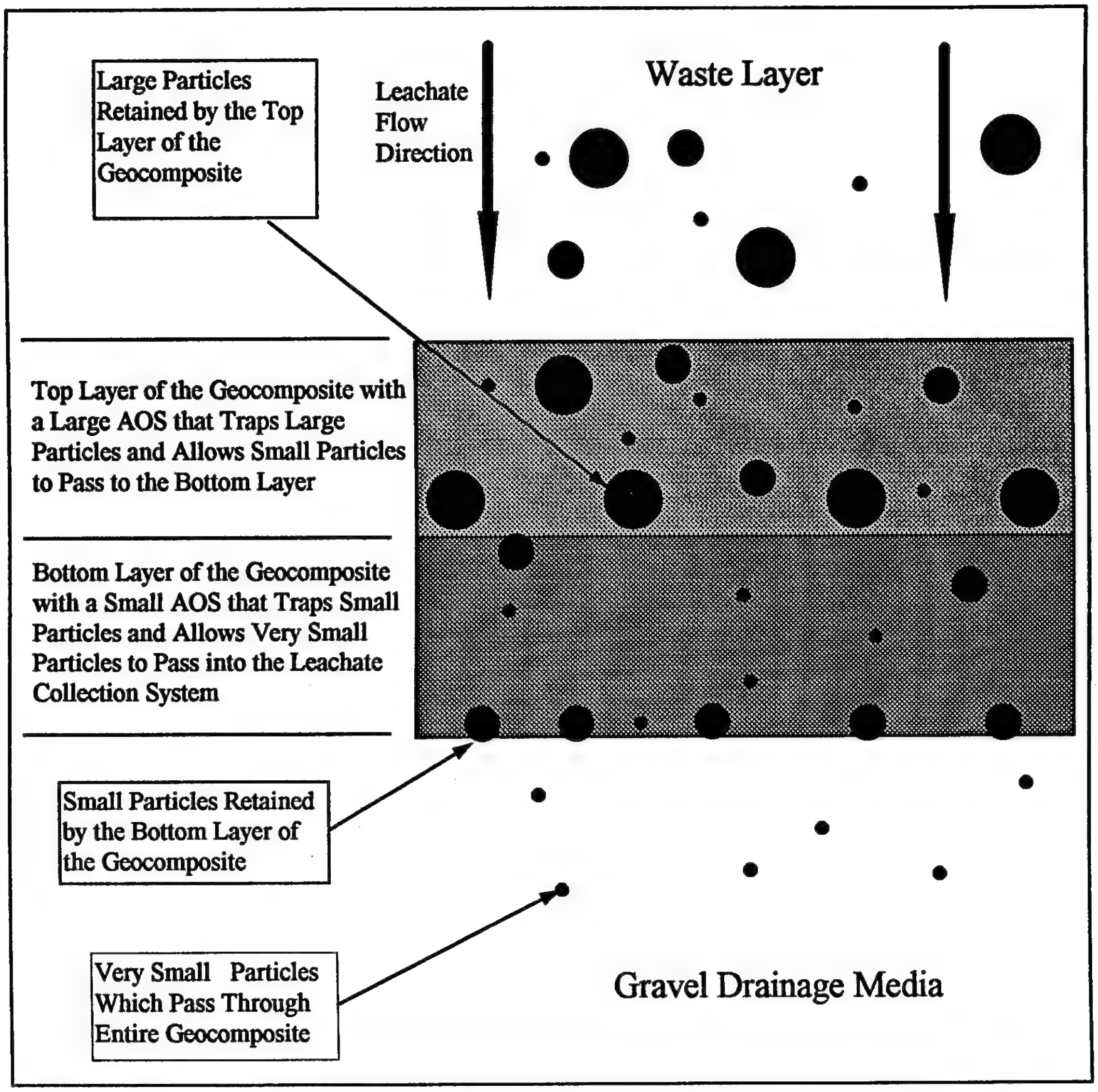


Figure 5.1: Filtration Action of the Geocomposite

There are an almost infinite possible number of combinations of geotextiles that could be bonded together to achieve this ends. Testing all possible combinations is beyond this research. The Koerner research has shown that landfill leachate has

relatively small particle sizes (39:71), therefore, a combination of geotextiles with small openings is necessary. Ronald M. Marsh of GeoComp, Inc., a leading distributor of geocomposites, recommended the use of the GT-80AP Geocomposite manufactured by Watersaver Company, Inc. of Denver, Colorado. Specific ASTM testing characteristics of this geocomposite are contained in Table 5.1 and a picture is contained in Figure 5.2. This particular Geocomposite is manufactured using both polypropylene and polyester fibers and is a nonwoven needle punched bonded fabric.

Table 5.1: Physical Properties of GT-80AP Geocomposite

Property	ASTM Test	Value
Weight (oz/yd^2)	D-3776	16
Thickness (mils)	D-1777	140
Grab Tensile (lbs)	D-4632	350
Elongation (%)	D-4632	70
Permittivity (1/sec)	D-4491	1.6
Puncture Resistance (lbs)	D-3787	225
Mullen Burst (psi)	D-3786	550
Trapazoidal Tear (lbs)	D-4533	150
Apparent Opening Size (U.S. Sieve)	D-4751	80 (top layer) 200 (bottom layer)

Source: (40)

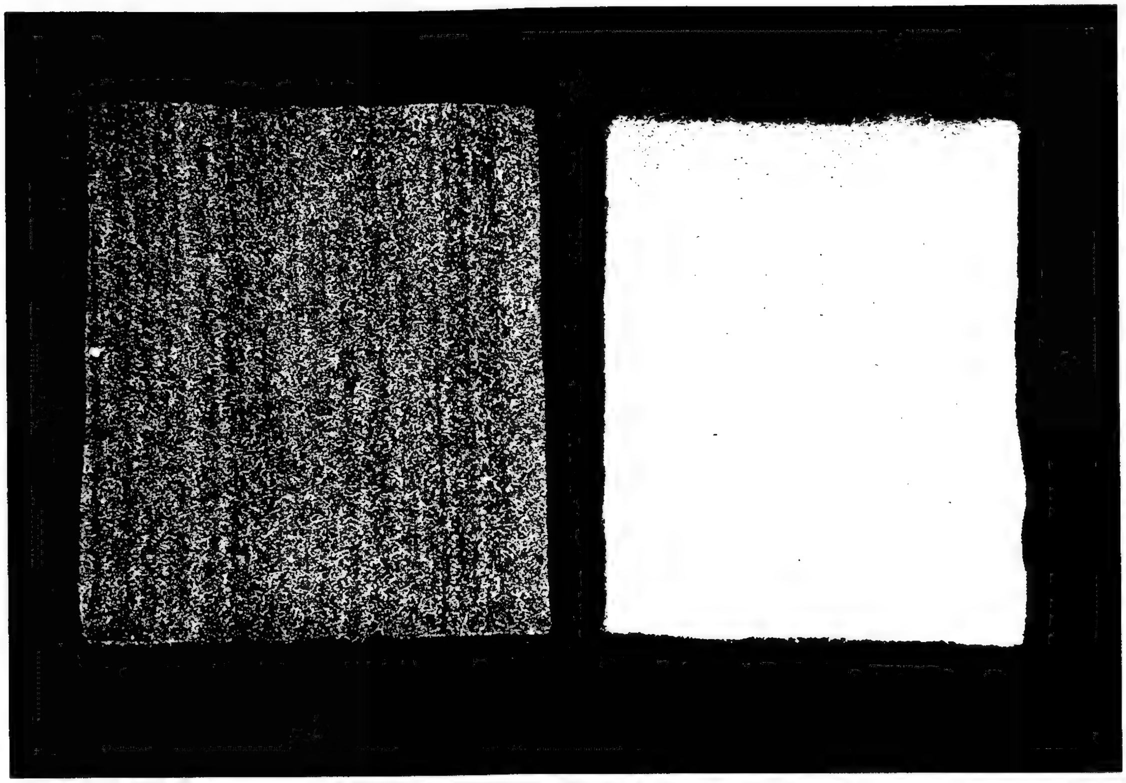


Figure 5.2: GT -80AP Geocomposite

CHAPTER 6 - EXPERIMENTAL PROCEDURE

6.1 General Procedure

The procedure involved in testing the four geotextiles and one geocomposite is contained in this chapter. The basic steps that were used are:

1. Mixed the synthetic leachate and set up the testing apparatus.

2. Tested all samples for initial permittivity.

3. Filtered a 30 day volume of leachate through each geotextile and the geocomposite.

4. Tested the filtered and unfiltered leachate for BOD_5, COD, TSS, iron and zinc to determine removal rates (%).

5. Retested permittivity.

6. Repeated steps 3 through 5 for a 60 and 90 day volume.

7. Repeated steps 1 through 6 three times with a high concentration leachate (leachate 1 for tests 1,2, and 3) and three times with a low concentration leachate (leachate 2 for tests 4, 5, and 6).

6.2 Characteristics and Mixing of Synthetic Leachate

6.2.1 Characteristics of Synthetic Leachate

In order to test the changes in concentration of the leachate as it passes through the geotextile filter, two different synthetic leachates will be tested; one that represents the high values found in the research shown in Table 3.2 and one that represents the low values. Leachate contaminant concentrations will be measured before filtration. Tap water will be used in mixing the synthetic leachate. The two leachates used are shown in Table 6.1 with the target unfiltered contaminant levels. Two contaminants have been added at intentionally high levels in the high concentration leachate: TSS concentration has been nearly doubled to ensure that the ultimate permittivity found by Koerner, is reached during the tests and zinc to ensure that any removal rate is seen at a statistically significant level.

Table 6.1: Proposed Concentrations in Leachate to be Tested

Leachate	BOD_5 (mg/l)	COD (mg/l)	TSS (mg/l)	Iron (mg/l)	Zinc (mg/l)
Summary of Leachate Constituent Research					
High from Table 3.2	25,000	45,000	16,000	1200	21.5
Low from Table 3.2	373	1167	204	20	.18
Summary of Proposed Synthetic Leachate					
Leachate #1(high conc.)	20,000	40,000	30,000	1200	65
Leachate #2(low conc.)	200	1000	200	14	0.1

6.2.1.1 TSS Load

Work done by Koerner (39:71-73) showed that landfill leachate particle sizes fall in a very narrow range. All of the suspended solids fell into the silt classification range, as they all pass the Number 200 U.S. Standard Sieve Size. The particles all fell into the range of .075 to .002 mm diameter. The synthetic leachate that will be mixed will include only soil particles that pass the Number 200 sieve in order to replicate this leachate. Colloidal kaolin was chosen because this clay like material falls into this silt classification range.

6.2.1.2 COD and BOD Load

Analysis of the causes of the COD are contained in research conducted by Robinson and Maris (31:31). They determined that volatile acids, acetic and proprionic, and the volatile fatty acid butyric were the cause of approximately 85 percent of the COD. An EPA study suggests these acid cause an even higher total (41:7). The remainder of the volatile fatty acids were not identified but the Robinson and Maris study stated they are mostly stearic or arachidic acids (31:143). For calculations in this study, stearic acid is used. There are also carbohydrates in various forms reported in the Robinson and Maris study. Glucose, a very common carbohydrate (in the form of dextrose monohydrate) will be added to replicate this.

To achieve the COD and BOD_5 levels desired, the acid mix contained in Table 6.2 was used. Each acid is in direct proportion to the acids found in actual leachate by Robinson and Maris. For example, Robinson and Maris found approximately 1700 mg/l of acetic acid in a leachate that had a COD of 23,800 mg/l. Since their COD is approximately half of what is desired for COD in Leachate #1, 3400 mg/l is added to leachate #1. These values are approximate and will achieve BOD_5 and COD values near those desired in Table 6.1. Actual measurements of BOD_5 and COD were made before filtering to confirm actual values in the synthetic leachate.

Table 6.2: Acid Mix to Produce Desired COD and BOD_5

Mixture	Acetic (mg/l) CH_3COOH	Proprionic (mg/l) C_2H_5COOH	Butyric (mg/l) C_3H_7COOH	Steric (mg/l) $C_{17}H_{35}COOH$	Glucose (mg/l) $C_6H_{12}O_6$
Leachate #1 (high conc.)	3400	3000	4000	8500	9400
Leachate #2 (low conc.)	70	60	80	170	200

6.2.2 Synthetic Leachate

The actual items used to mix the synthetic leachate are shown in Figure 6.1. All were reagent grade except the iron chloride which was technical grade. In order to obtain the leachate described in Table 6.1, two stock solutions of 15 liters each were mixed in polyethelene containers. One contained the components to produce the TSS and metals load and the other the acids to produce the BOD_5 and COD loads.

6.2.2.1 TSS and Metals Stock Solution

The TSS and Metals stock solution was produced by adding the contaminants shown in Table 6.3 to the 15 liters of tap water. The desired concententration column refers to the stock solution concentration which is double the concentration desired in the leachate that will be filtered.

Table 6.3: TSS and Metals Stock Solution

Metal	Leachate	Conc. (mg/l)	Form	Weight added to 15 liters
Iron	1 (high conc.)	2400	$FeCl_3*6H_20$	202.9 grams
	2 (low conc.)	28	$FeCl_3*6H_20$	2.03 grams
Zinc	1 (high conc.)	130	$Zn(NO_3)_2*6H_20$	8.91 grams
	2 (low conc.)	0.3	$Zn(NO_3)_2*6H_20$	0.001 grams
colloidal	1 (high conc.)	60,000	clay	600 grams
kaolin	2 (low conc.)	400	clay	6 grams

6.2.2.2 Organic Stock Solution

In the other container the acetic, proprionic, butyric, and stearic acids as well as the dextrose monohydrate were added in the condition and quantities shown in Table 6.4. This container with the organic acids was kept under a fume hood to mitigate excessive odors

6.2.2.3 Final Synthetic Waste

When an actual leachate sample was needed for filtration, equal volumes were drawn from each container, mixed, and filtered.

Table 6.4: Organic Acid Stock Solution

Substance	Leachate	Conc. (mg/l)	Density (kg/l)	Amount Added to 15 l.
Acetic	1 (high conc.)	6800	1.05	97.1 ml
	2 (low conc.)	140	1.05	2.0 ml
Proprionic	1 (high conc.)	6000	.99	90.9 ml
	2 (low conc.)	120	.99	1.8 ml
Butyric	1 (high conc.)	8000	.96	125 ml
	2 (low conc.)	160	.96	2.5 ml
Steric	1 (high conc.)	17000	N/A	255 grams
	2 (low conc.)	340	N/A	5.1 grams
Dextrose as	1 (high conc.)	18800	N/A	310.2 grams
$C_6H_{12}O_6*H_2O$	2 (low conc.)	400	N/A	6.6 grams

Figure 6.1: Mix for Synthetic Leachate

6.3 Leachate Production Rate Modeled with Synthetic Leachate

As discussed in Chapter #3, no landfill was found to produce more than 5000 liters of leachate per hour per hectare. Koerner found in his research that geotextiles reached their ultimate, very low flow rates after approximately 60 days of flow. The total time frame of this model will be 90 days to ensure that the ultimate permittivity is reached. To simulate leachate filtration, a 90 day flow volume, based on a flow rate of 5000 l/ha/hr and the area of the test samples will be used (for a 8.3 cm diameter sample, as will be used in this test, a 90 day flow volume equals 5.85 liters) Tests of the contaminants will be conducted after each thirty day volume (1.95 liters) of leachate flows through the geotextile. It is important to note that thirty days will not actually pass between samples.

6.4 Experimental Testing Apparatus

The experimental testing apparatus is shown in Figure 6.2 through Figure 6.4. Figure 6.2 shows the leachate flow device used to model leachate filtration. Figure 6.3 shows in detail the geotextile containment profile. Figure 6.4 shows one tube of the modified apparatus which is used to test the permittivity of the geotextile.

6.4.1 Leachate Flow Device

The Leachate Flow Device, shown in action in Figure 6.7, is set up to allow a 30 day volume of leachate to pass through each of the five sampling ports at a time. In the leachate flow device, the area of the sample is 54.11 cm^2, so 1.945 liters must pass though the sample to replicate the 30 days of flow. The geotextile sample installed in the containment ring is shown in Figure 6.5. PVC pipe is placed above and below the sample. The pipe above the sample is a total of 28 cm high to include the various connections. Details of the connections is contained in Figure 6.3. The pipe below is 13 cm high and contains large aggregate gravel to provide support for the sample. This is shown in Figure 6.6. The PVC pipe is 10.16 cm in diameter. A rubber gasket is placed around the sample as well as a seal to ensure that the joints are all water proof. Once the geotextile and seals are in place, the top and bottom are bolted together using four 0.25 inch machine screws. At the bottom of the lower pipe a cap is cemented on with a 1.25 inch diameter hole drilled. A tube is connected to this hole that runs to the outflow reservoir. When testing begins, 1.95 liters of leachate is poured down the side of the upper pipe. It runs through the filter and out the lower tube into the outflow reservoir. Here the leachate can is drawn for sampling and testing. Note that work done in this configuration was conducted under a fume hood to mitigate odors.

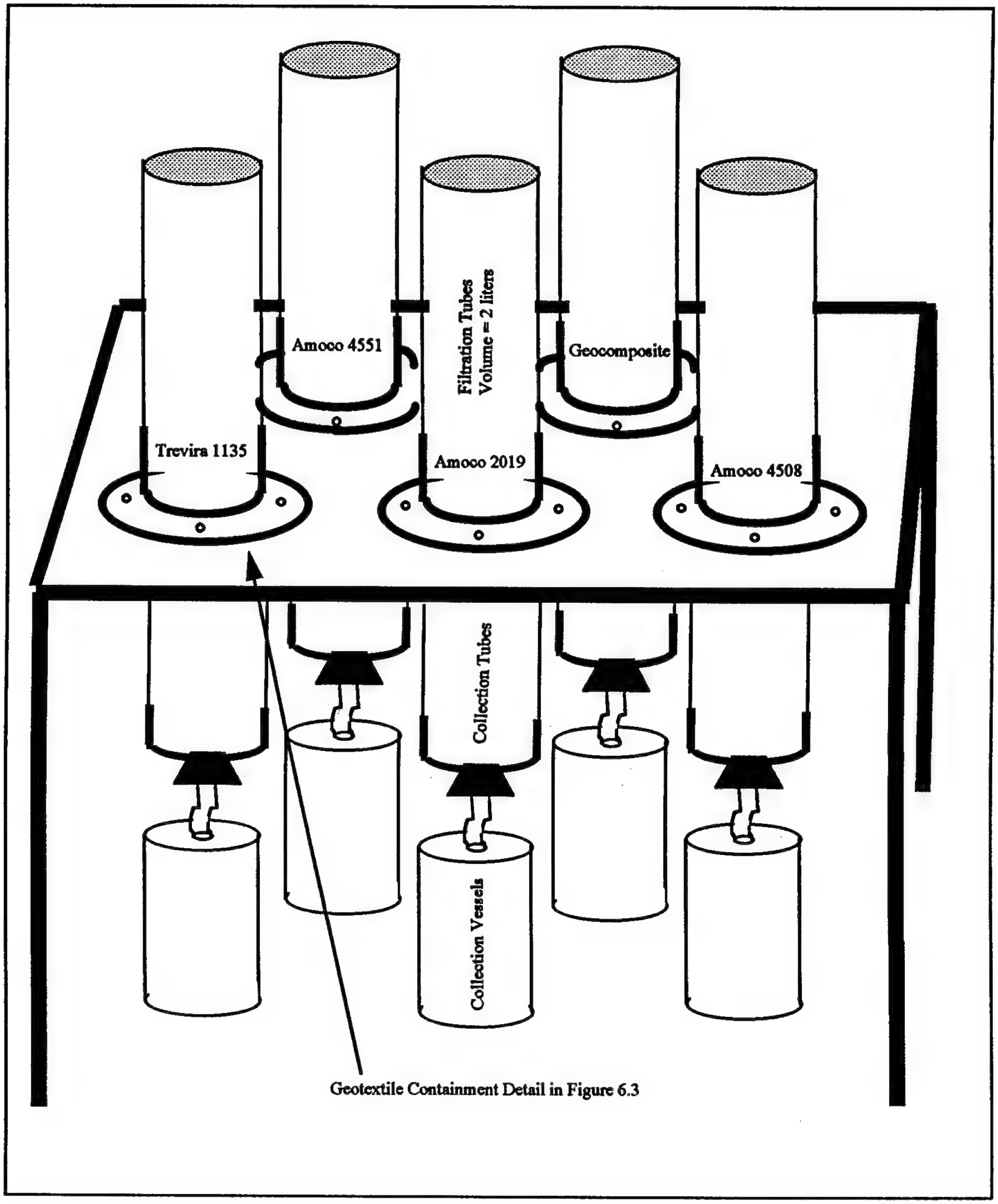


Figure 6.2: Filtration Apparatus

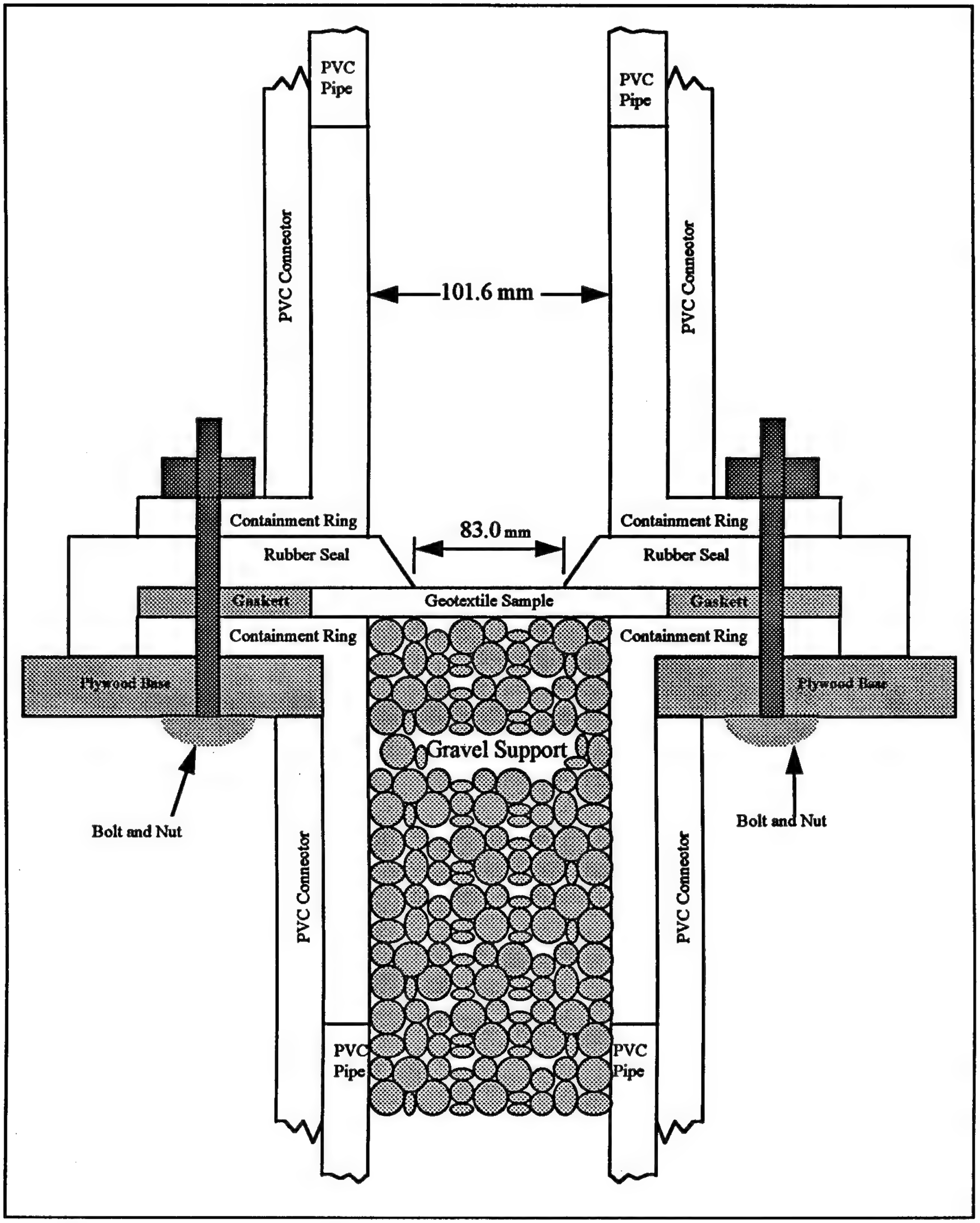


Figure 6.3: Geotextile Containment Detail

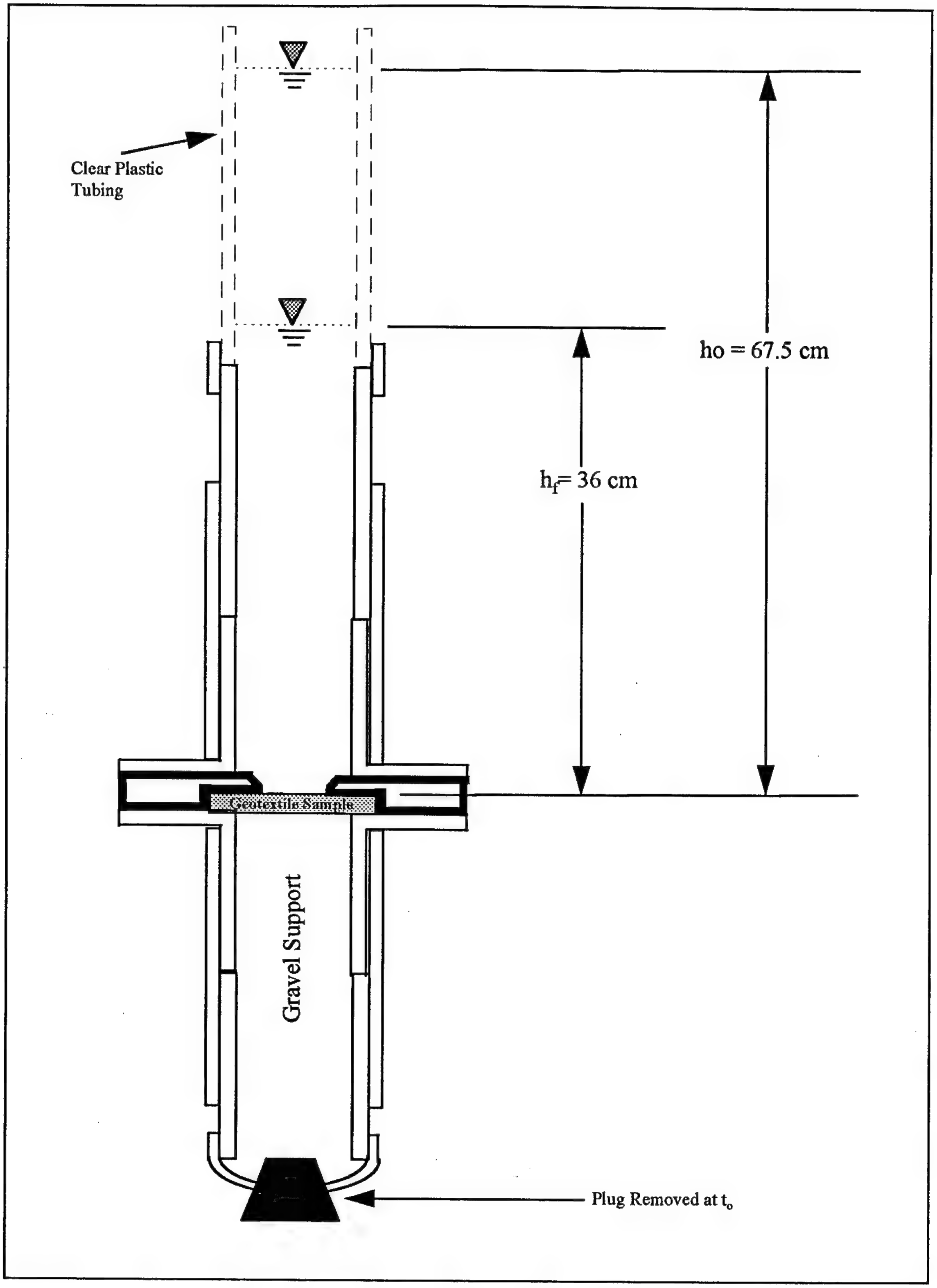


Figure 6.4 Filtration Apparatus Modified for Permittivity Testing

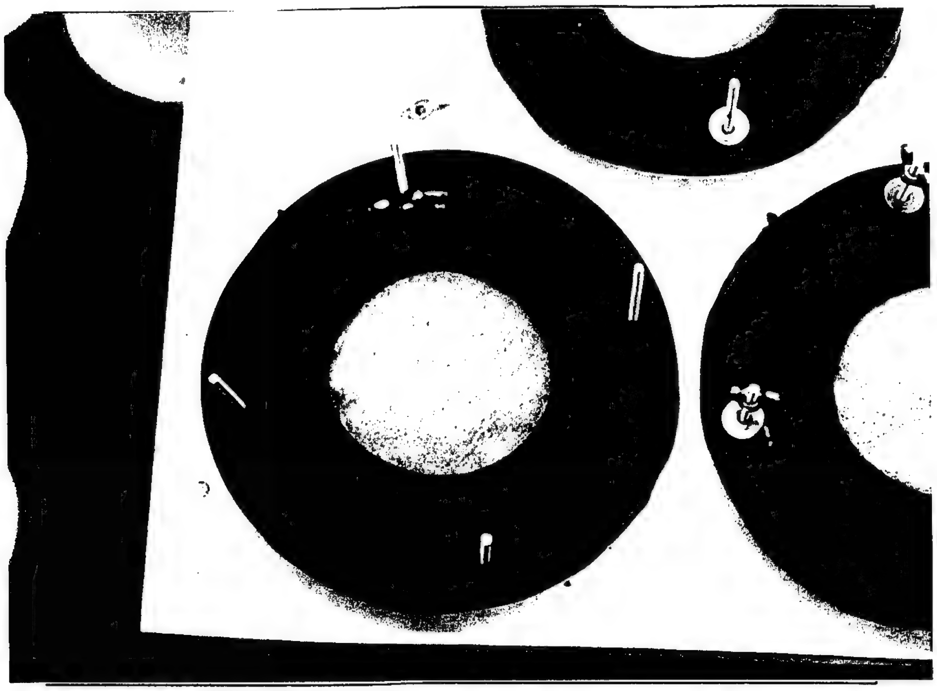


Figure 6.5: Geotextile Sample Installed in Containment Ring

Figure 6.6 Gravel Support Media for Geotextile

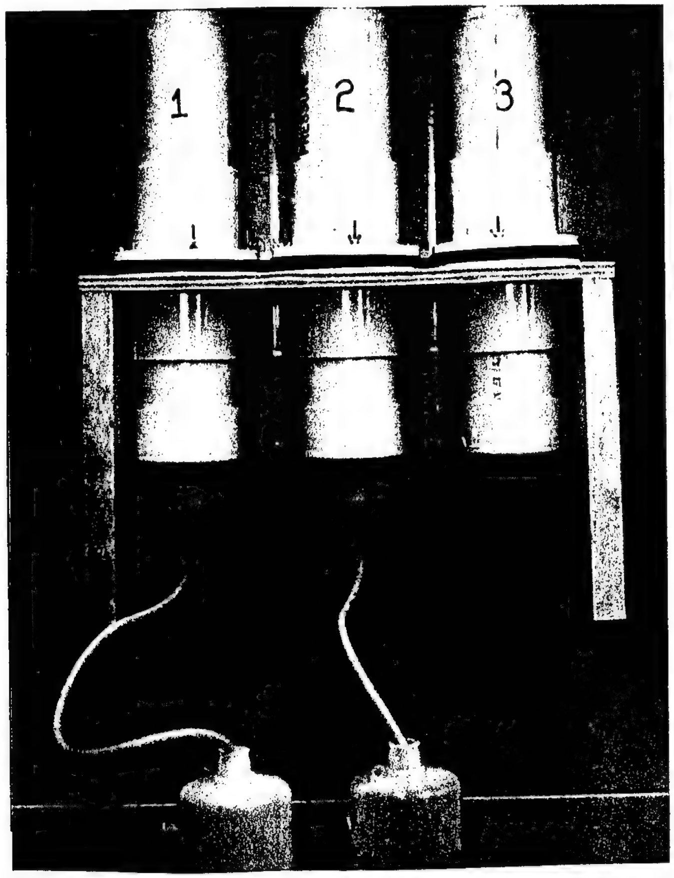


Figure 6.7 Leachate Flow Devices in Action

6.4.2 Leachate Flow Device Modified for Permittivity Testing

The permittivity test was conducted in accordance with the ASTM Test D 1987-91, Standard Test Method for Biological Clogging of Geotextile or Soil, Geotextile Filters (35:1). Actual testing is shown in Figure 6.8. Each sample was tested individually and the setup of each tube is shown in Figure 6.4. The sampling tubes at the bottom of the device were removed and plugged. A clear tube approximately 40 cm high was placed on the top of the upper pipe using a PVC connector. Two lines are drawn on the pipe to represent h_o and h_f. The entire tube is

then filled with water up to the h_o line. The plug in the lower end cap is then removed. The time is then measured for the water level to reach the h_f line. The permittivity was then determined using this application of the Darcy equation:

$$\psi = (2.3 * a / (A * \Delta t)) * \log_{10} (h_o / h_f)$$

Where: ψ = permittivity (sec^{-1})
a = area of liquid supply standpipe ($89.92 cm^2$)
A = area of test specimen ($54.11 cm^2$)
Δt = time change between h_o and h_f (sec)
h_o = head at beginning of test
h_f = head at end of test

Note that the permeability of the test specimen can be calculated by the following equation:

$$k = \psi * t$$

Where: k = coefficient of permeability (cm/sec)
ψ = permittivity (sec^{-1})
t = thickness of the sample (cm)

During actual testing, h_o and h_f values varied. The actual values of h_o and h_f are reported in Appendix E.

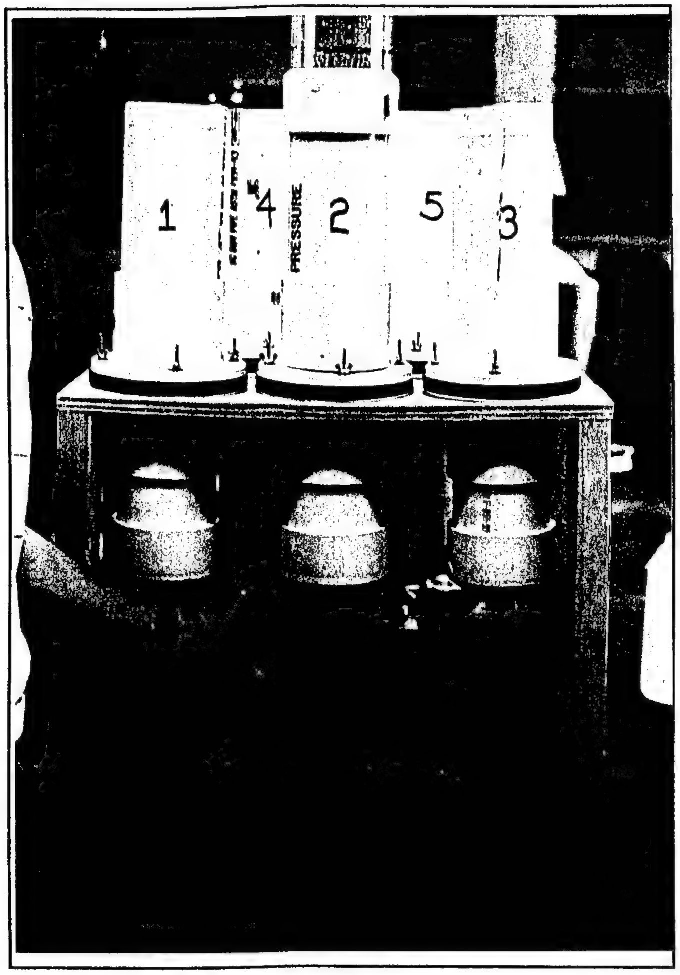


Figure 6.8: Leachate Flow Device Modified for Permittivity Testing

6.5 Testing for BOD_5, COD, TSS, Zinc, and Iron

The detailed procedures for BOD_5, COD, TSS, and metals analysis are contained in Appendices A, B, C, and D. All testing was conducted in accordance with the *Standard Methods for the Examination of Water and Waste Water*. They are also

depicted in Figures 6.10 through 6.11. Each of these contaminants were analyzed before and after filtration. The filtered leachate was tested after 30, 60, and 90 day volumes of flow. Figures 6.9 through 6.11 show these tests being conducted.

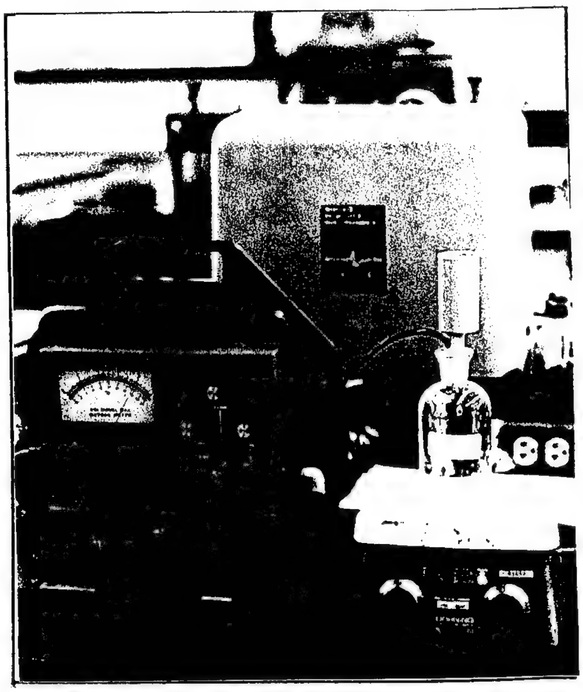


Figure 6.9: Measuring DO for BOD Test

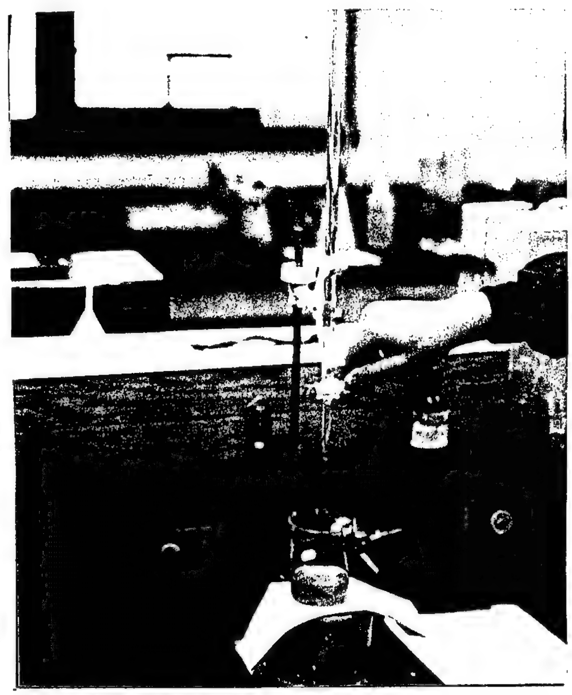


Figure 6.10: Titration Conducted in COD Test

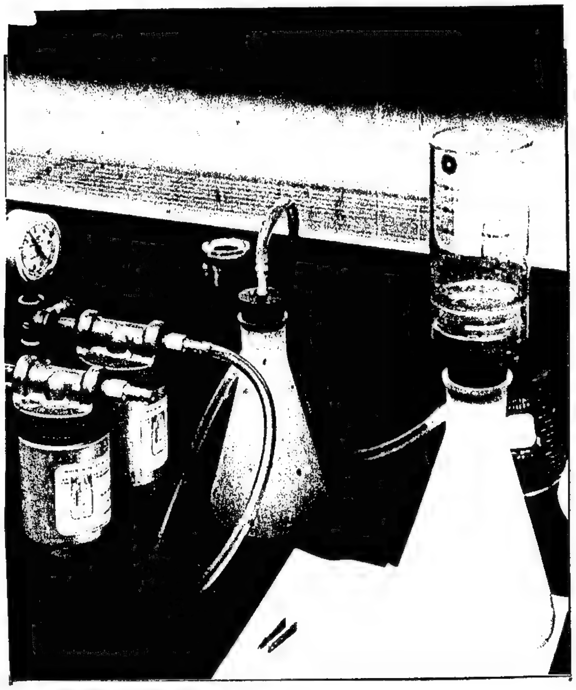


Figure 6.10: Vacuum Applied in the Total Suspended Solids Test

Figure 6.11: Measuring Absorbencies on the Atomic Spectrometer

6.6 Test Duplication for Statistical Analysis

In order to conduct a statistical analysis, each geotextile test was duplicated three times. For each individual test, all contaminants and permittivity were measured r five times, with the exception of several BOD_5 samples which were tested with two or three samples during the high concentration leachate. BOD5 results are in Appendix A. When the time change in the permittivity test was greater than 5000 seconds, it was only measured once instead of five times. These procedures were followed after each thirty day equivalent volume of leachate was passed.

CHAPTER 7 - EXPERIMENTAL RESULTS

7.1 General

A statistical analysis of the results is contained in this chapter. An example of a table used to portray the results is contained in Table 7.1. Each geotextile in the table is ordered with the most favorable result on top and the least favorable on the bottom. For contaminant removal, this means that the top geotextile removed the most of that contaminant. For permittivity, it means the geotextile on top has the highest permittivity. From Table 7.1, after a 30 day volume, the Trevira 1135 performed this sample test the most favorably and the Amoco 2019, the least favorably. The other three geotextiles are ranked appropriately The mean for each constituent is displayed with the 95% confidence interval. T-tests results were conducted at a 95% confidence level. Geotextiles that did not show a statistically significant difference (i.e. their t-test results showed them to be equal) for a particular parameter, are grouped together. Their individual means and 95% confidence intervals are shown, and the overall mean for the group is shown directly to the right. For example, from Table 7.1, after a 30 day volume of flow, the Amoco 4551 and the Geocomposite did not show statistically significant differences in Constituent A and their overall mean is 1.52. Likewise, after a 60 day volume of flow, only the Geocomposite showed a statistically more favorable performance with regards to Constituent A. The others are grouped together and their overall mean of $2.55\text{x}10^{-5}$ shown. Lastly, constituent removals that were not

statistically significant compared to unfiltered leachate, are shown in tables in italics and shaded. The Trevira 2019 at 30 and 60 days in Table 7.1 is an example of this.

Other tables are used which are self explanatory as well as various XY scatter plots. Note that most analysis of the results is based on data from tables and the graphs are added for clarity. Actual results of the experiments are contained in Appendix A (BOD_5 Results), Appendix B (COD Results), Appendix C (TSS Results), Appendix D (Metals Results), Appendix E (Permittivity Results), and Appendix F (Filter Cake Analysis Results).

Table 7.1: Example Constituent Analysis Table

<table>
<tr><th>Geotextile</th><th colspan="2">Constituent A - 30 Days (Units)</th><th>Geotextile</th><th colspan="2">Constituent A - 60 Days (Units)</th></tr>
<tr><td>Trevira 1135</td><td colspan="2">1.64±0.08</td><td>Geocomp</td><td colspan="2">$0.043 \pm 1.8x10^{-2}$</td></tr>
<tr><td>Amoco 4551</td><td>1.53±0.05</td><td rowspan="2">1.52</td><td>Amoco 4551</td><td>$4.26x10^{-5} \pm 5.32x10^{-4}$</td><td rowspan="4">$2.55x10^{-5}$</td></tr>
<tr><td>Geocomp</td><td>1.51±0.06</td><td>Amoco 4058</td><td>$2.38x10^{-5} \pm 4.34x10^{-4}$</td></tr>
<tr><td>Amoco 4058</td><td colspan="2">1.17±0.01</td><td>Trevira 1135</td><td>$2.29x10^{-5} \pm 4.79x10^{-4}$</td></tr>
<tr><td>Amoco 2019</td><td colspan="2">0.06±0.01</td><td>Amoco 2019</td><td>$1.26x10^{-5} \pm 1.48x10^{-4}$</td></tr>
</table>

7.2 Values of all Contaminants Obtained for Unfiltered Leachate

Table 7.2 shows the values of the unfiltered leachate that were obtained in comparison to those desired as outlined in Chapter 3. The low concentration COD

and Zinc were the only contaminants whose confidence interval fell outside the proposed concentration. Because results are reported on a percent removal basis, they are still used to evaluate removal efficiency. Removal percentages throughout this chapter are based on values remaining in the filtered leachate and values obtained for the unfiltered leachate.

Table 7.2: Unfiltered Leachate Concentrations

	High Concentration Leachate			Low Concentration Leachate		
Constituent	Proposed	Mean	Conf Inter	Proposed	Mean	Conf Inter
BOD_5 (mg/l)	20,000	21,400	±1800	200	199	±9
COD (mg/l)	40,000	40,100	±2750	1000	390	±48
Total Susp Solid (mg/l)	30,000	34,400	±5100	200	224	±7
Iron (mg/l)	1200	1165	±107	14	13.7	±4
Zinc (mg/l)	65	102	±0.5	0.1	0.21	±0.08

7.3 Permittivity Results

The permittivity of all four geotextiles and the the geocomposite decrease with the amount of leachate volume filtered. High concentration leachate results in extreme loss of permittivity as shown in Figure 7.1. Low concentration leachate permittivity changes are less dramatic as shown in Figure 7.2. Actual results of the permittivity testing are contained in Tables 7.3 and 7.4.

At high concentration, the Geocomposite was the only sample that statistically outperformed the others and this was only after a 30 day volume of flow. After the 30 day volume of flow, it retained a permittivity that was several orders of magnitude higher than the other four samples. This changed after 60 and 90 days of flow, as all five samples retained a statistically equal amount of permittivity.

At the low concentration, the Trevira 1135 consistently outperformed the other samples. Its permittivity was the highest after each volume of leachate was passed through the samples. Likewise, the Amoco 2019 was consistently outperformed by all the other samples at low concentration. The Geocomposite, Amoco 4058, and the Amoco 4551 did not at any volume show any statistically significant difference in their permittivities once leachate flow was initiated.

Table 7.3: Results of Permittivity Testing at High Concentration

<table>
<tr><th>Geotextile</th><th colspan="2">Permittivity - 0 Days (1/sec)</th><th>Geotextile</th><th colspan="2">Permittivity - 30 Days (1/sec)</th></tr>
<tr><td>Trevira 1135</td><td colspan="2">1.64±0.08</td><td>Geocomp</td><td colspan="2">0.043±1.8x10^{-2}</td></tr>
<tr><td>Amoco 4551</td><td>1.54±0.05</td><td rowspan="2">1.53</td><td>Amoco 4551</td><td>3.95x10^{-5}±1.46x10^{-5}</td><td rowspan="4">2.26x10^{-5}</td></tr>
<tr><td>Geocomp</td><td>1.52±0.06</td><td>Amoco 4058</td><td>2.20x10^{-5}±1.34x10^{-5}</td></tr>
<tr><td>Amoco 4058</td><td colspan="2">1.17±0.01</td><td>Trevira 1135</td><td>1.63x10^{-5}±5.85x10^{-6}</td></tr>
<tr><td>Amoco 2019</td><td colspan="2">0.06±0.01</td><td>Amoco 2019</td><td>1.11x10^{-5}±1.39x10^{-5}</td></tr>
</table>

Table 7.3: Results of Permittivity Testing at High Concentration (Cont.)

Geotextile	Permittivity - 60 Days (1/sec)		Geotextile	Permittivity - 90 Days (1/sec)	
Geocomp	$1.10 \times 10^{-5} \pm 4.72 \times 10^{-6}$		Geocomp	$6.66 \times 10^{-6} \pm 2.60 \times 10^{-7}$	
Amoco 4551	$9.48 \times 10^{-6} \pm 4.82 \times 10^{-6}$		Amoco 4058	$6.46 \times 10^{-6} \pm 2.69 \times 10^{-6}$	
Trevira 1135	$9.06 \times 10^{-6} \pm 1.56 \times 10^{-6}$	8.70×10^{-6}	Amoco 4551	$6.19 \times 10^{-6} \pm 7.52 \times 10^{-7}$	6.02×10^{-6}
Amoco 4058	$8.07 \times 10^{-6} \pm 2.51 \times 10^{-6}$		Trevira 1135	$6.19 \times 10^{-6} \pm 4.72 \times 10^{-7}$	
Amoco 2019	$5.91 \times 10^{-6} \pm 3.52 \times 10^{-6}$		Amoco 2019	$4.58 \times 10^{-6} \pm 1.75 \times 10^{-6}$	

Table 7.4: Results of Permittivity Testing at Low Concentration

Geotextile	Permittivity - 0 Days (1/sec)		Geotextile	Permittivity - 30 Days (1/sec)	
Trevira 1135	1.67±0.01		Trevira 1135	1.54±0.05	
Amoco 4551	1.45±0.07		Geocomp	1.12±0.07	
Geocomp	1.24±0.04	1.23	Amoco 4551	0.86±0.34	0.86
Amoco 4058	1.22±0.12		Amoco 4058	0.59±0.22	
Amoco 2019	0.05±0.006		Amoco 2019	0.02±0.01	

Geotextile	Permittivity - 60 Days (1/sec)		Geotextile	Permittivity - 90 Days (1/sec)	
Trevira 1135	1.48±0.07		Trevira 1135	1.42±0.11	
Geocomp	0.99±0.07		Geocomp	0.82±0.03	
Amoco 4551	0.75±0.34	0.75	Amoco 4551	0.70±0.30	0.65
Amoco 4058	0.50±0.20		Amoco 4058	0.44±0.19	
Amoco 2019	0.01±0.004		Amoco 2019	0.005±0.001	

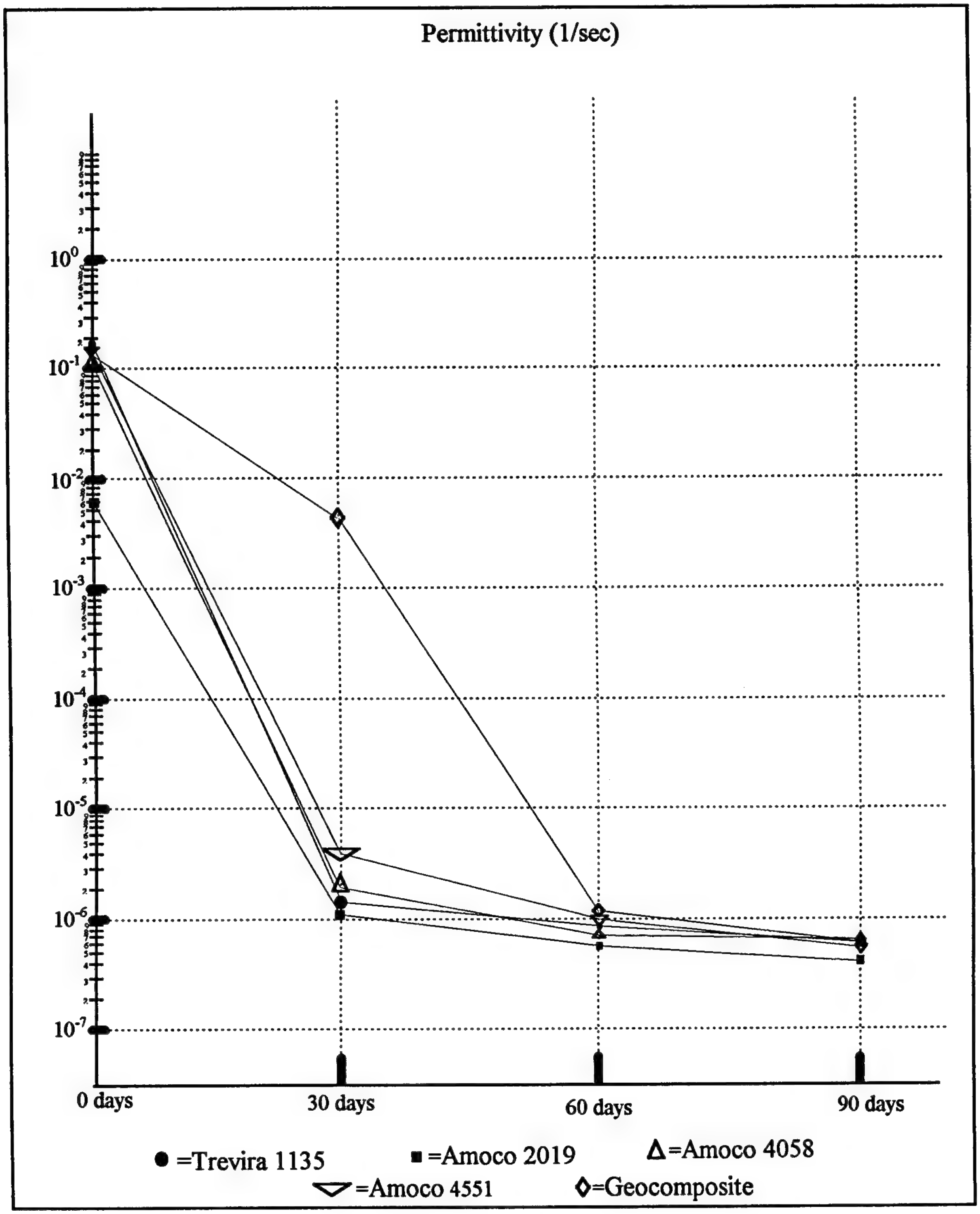


Figure 7.1: Permittivity versus Time for all Geotextiles with High Concentration Leachate

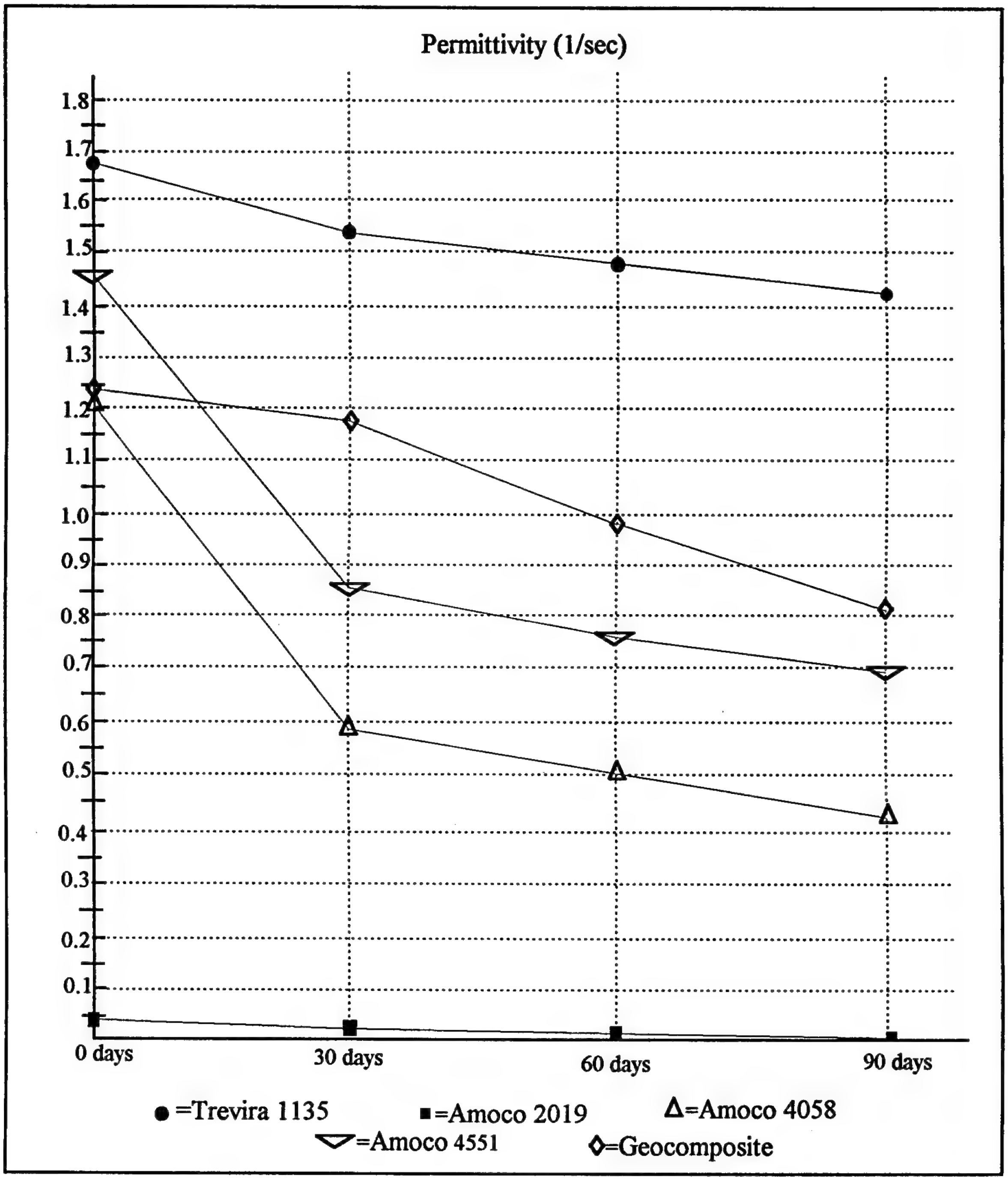


Figure 7.2: Permittivity versus Time for all Geotextiles with

Low Concentration Leachate

Tables 7.5 and 7.6 show the percent permittivity that each geotextile retains as up to 90 days of leachate volume at high and low concentration pass though it. The Geocomposite retains the highest percent (2.8%) of its original permittivity after a 30 day volume of high concentration leachate flow. The Amoco 2019 maintained the most after 60 and 90 day volumes, but it is important to keep in mind that it started with the lowest permittivity. Under low concentration flow the Trevira 1135 kept the largest amount of its original permittivity, further suggesting that it is the best product for low concentration leachate flow.

Table 7.5: Retention of Original Permittivity after High Concentration Leachate Flow

Volume	Trevira 1135	Amoco 2019	Amoco 4058	Amoco 4551	Geocomposite
30 Days	9.94×10^{-4}%	1.84×10^{-2}%	1.88×10^{-3}%	2.56×10^{-3}%	2.8%
60 Days	5.51×10^{-4}%	9.77×10^{-3}%	6.91×10^{-4}%	6.14×10^{-4}%	7.21×10^{-4}%
90 Days	3.76×10^{-4}%	7.58×10^{-3}%	5.53×10^{-4}%	4.01×10^{-4}%	4.37×10^{-4}%

Table 7.6: Retention of Original Permittivity after Low Concentration Leachate Flow

Volume	Trevira 1135	Amoco 2019	Amoco 4058	Amoco 4551	Geocomposite
30 Days	92.2%	50.9%	48.7%	59.1%	90.1%
60 Days	88.8%	21.2%	41.4%	51.9%	79.6%
90 Days	85.3%	9.1%	35.7%	47.9%	65.7%

7.4 Comparison of Permittivity with Results from the Geosynthetic Research Institute Study

Koerner, Koerner, and Martin reported in "Design of Landfill Leachate-Collection Filters" (12:1792-1803) the permeability of a geotextile after up to 200 days of leachate flow. They show graphs of the decreasing permeability for an 8 oz/yd^2 needle punched nonwoven geotextile. The Amoco 4058 used in this research is also an 8 oz/yd^2 needle punched nonwoven geotextile so the permeability's are compared here.

The Koerner research used three different leachates. The contaminant levels in each are given in Table 7.7 along with values obtained for the synthetic leachates mixed in this study. The D, P, and L are designations given by Koerner.

Table 7.7: Contaminant Levels of Leachate Used in Koerner Research

	Koerner Study			Koenig Study	
Leachate	D	P	L	High Conc	Low Conc
TSS (mg/l)	13,900	5,000	35,000	34,400	224
BOD5 (mg/l)	19,000	2,400	900	21,400	199
COD (mg/l)	30,000	6,300	3,100	40,000	390
Flow (L/hr/ha)	7,000			5,000	

Source: (42)

In the Koerner study, permeability of the samples is reported. Here, permittivity was determined, so, in order to compare the two, data from this study is converted to permeability. The method of conversion from permittivity to permeability is given in Section 6.3.2. An example conversion is given in Appendix G. The thickness of the Amoco 4058 is 115 mils (0.2875 cm).

As shown in Table 7.7 Koerner modeled a leachate flow rate of 7,000 liter per hour per hectare. In order to compare the results, overall TSS flow amounts are used instead of time. For instance, Leachate L of the Koerner study applies the same amount of TSS to the geotextile in 42 days as the high concentration leachate does at 90 days, so the permeability's are compared at these two points.

The permeability of the geotextiles under four different leachate flows (Koerner leachates D, P, and L, and Koenig high concentration) are plotted in Figure 7.3 against the TSS load applied to each. Leachate P can only be plotted as shown because this is the maximum TSS load applied by this leachate reported by Koener. All four follow very similar paths. The permeability in Leachate D falls consistently into the confidence interval presented in Table 7.3 for the Amoco 4058. Leachate P is slightly outside but the overall slopes are very similar. The permeability's of the Koerner samples start out higher than the Amoco 4058 and maintain the approximate same difference throughout testing. For these reasons, the results of this study and the Koerner study are considered consistent.

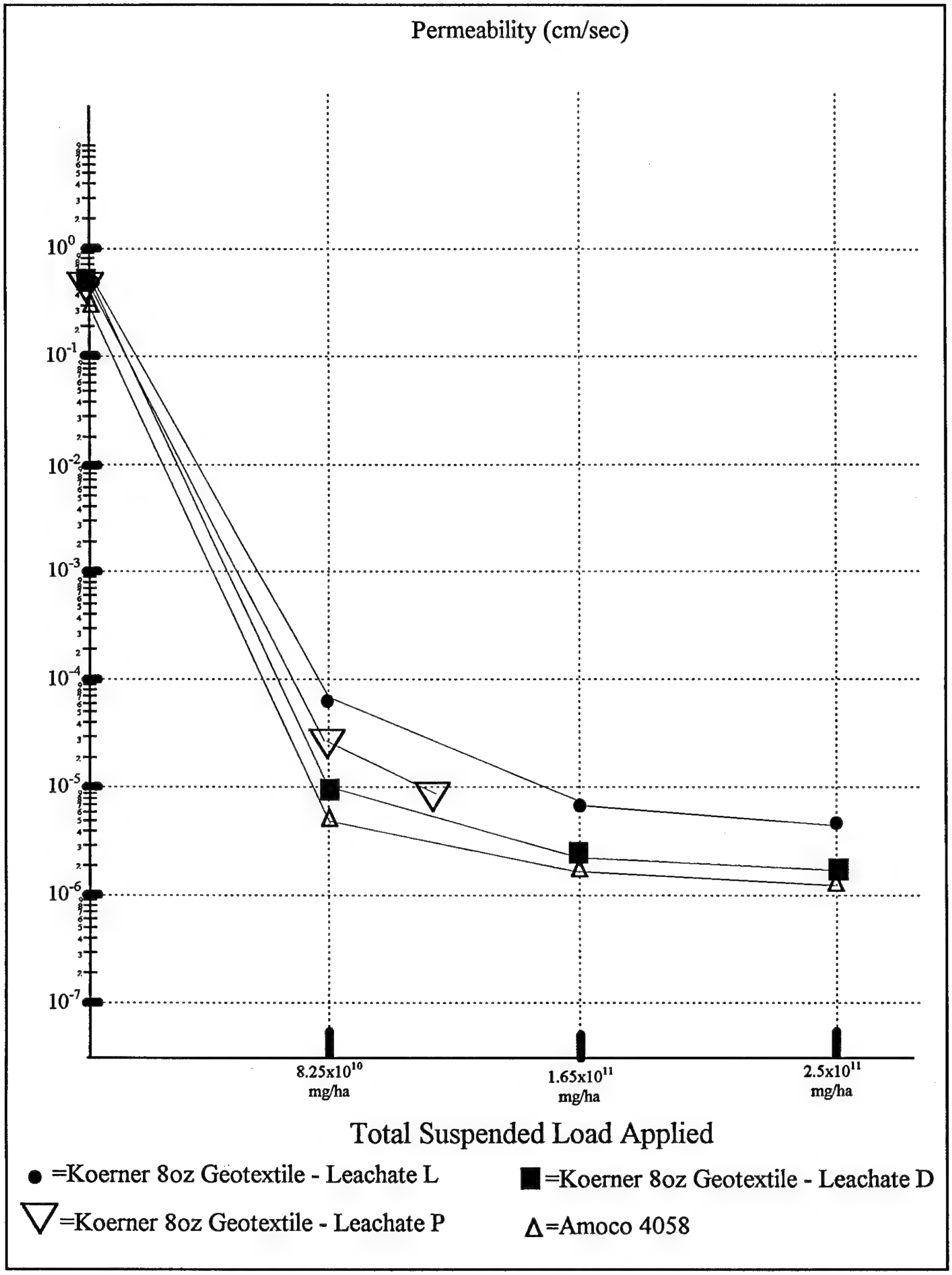


Figure 7.3: Permeability versus. TSS Load

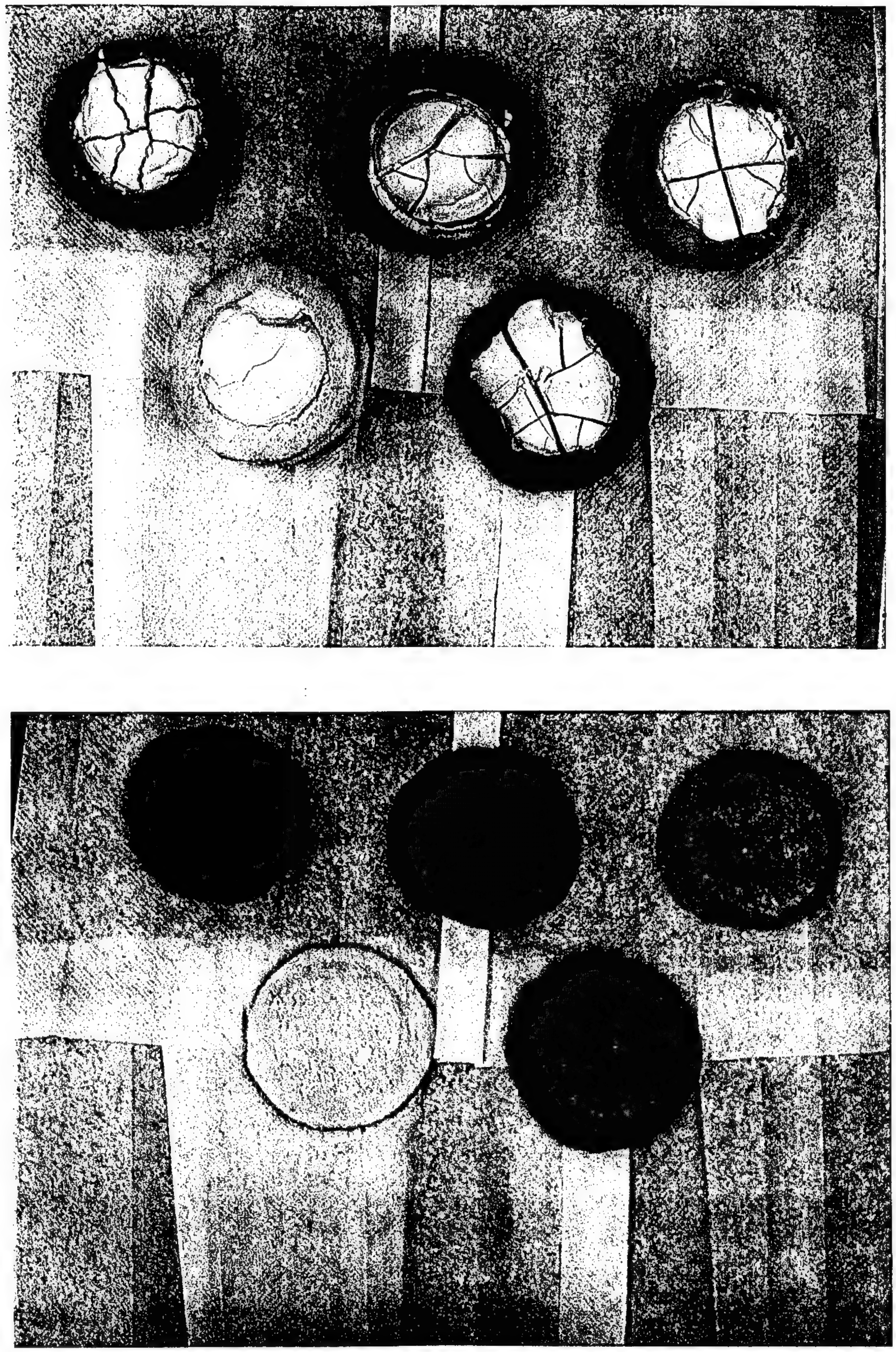


Figure 7.4: Geotextiles after 90 Day Volumes of High Concentration Flow (Note: Cracking is due to drying after experiments) and Low Concentration Flow

7.5 Biochemical Oxygen Demand Removal

Synthetic leachate used in tests 1, 2, and 3 had an average BOD_5 of 21,387 mg/l. Tests 4, 5, and 6 had an average BOD_5 of 199 mg/l. In all tests, geotextile removal rates were low. Removal rates ranged anywhere from 22 percent to approximately zero. There no statistical difference in removal rates based increasing equivalent flow volumes.

Figures 7.5 and 7.6 plot the BOD_5 removal percentages versus the leachate volume of flow of high and low concentration leachate respectively. These show the rather random nature of the removals, particularly under high concentration conditions. Tables 7.8 and 7.9 show the statistical analysis of the BOD_5 filtration. At high concentration, only the Trevira 1135 at 30 days, the Amoco 4551 and Trevira 1135 at 60 days, and the Trevira 1135 at 90 days showed any statistically significant ability to remove BOD_5 from the leachate. At low concentration, no geotextile showed any statistically significant ability to remove BOD_5. The other important statistic from Tables 7.8 and 7.9 is the fact that no geotextile outperformed another in a statistically significant manner at either high or low concentrations. From this research, it is seen that these geotextiles do not remove a statistically significant amount of BOD_5.

Table 7.8: BOD_5 Removal Percentages for High Concentration Leachate

Geotextile	BOD_5 Removed - 30 Days (%)		Geotextile	BOD_5 Removed - 60 Days (%)		Geotextile	BOD_5 Removed - 90 Days (%)	
Trevira 1135	15.9± 5.0		Amoco 4551	22.0± 15.4		Trevira 1135	21.0± 6.6	
Amoco 4058	14.9± 6.2		Trevira 1135	21.0± 4.6		Amoco 4058	12.3± 10.3	
Amoco 2019	8.7± 11.3	10.5	Geocomp	16.2± 29.5	14.6	Geocomp	11.6± 12.2	11.7
Amoco 4551	7.4± 21.0		Amoco 2019	11.7± 12.0		Amoco 2019	11.4± 6.4	
Geocomp	5.5± 5.7		Amoco 4058	2.2± 5.8		Amoco 4551	2.3± 12.3	

Table 7.9: BOD_5 Removal Percentages for Low Concentration Leachate

Geotextile	BOD_5 Removed - 30 Days (%)		Geotextile	BOD_5 Removed - 60 Days (%)		Geotextile	BOD_5 Removed - 90 Days (%)	
Amoco 4551	8.2± 8.2		Geocomp	18.6± 9.3		Geocomp	13.4± 5.7	
Trevira 1135	6.8± 5.0		Amoco 4058	9.0± 13.8		Amoco 4058	10.5± 7.8	
Geocomp	6.6± 7.6	5.0	Amoco 4551	6.0± 6.1	8.1	Amoco 4551	8.4± 8.7	7.8
Amoco 2019	3.8± 4.9		Trevira 1135	5.9± 1.1		Trevira 1135	4.7± 5.6	
Amoco 4058	-0.22± 12.3		Amoco 2019	1.2± 6.7		Amoco 2019	2.0± 3.9	

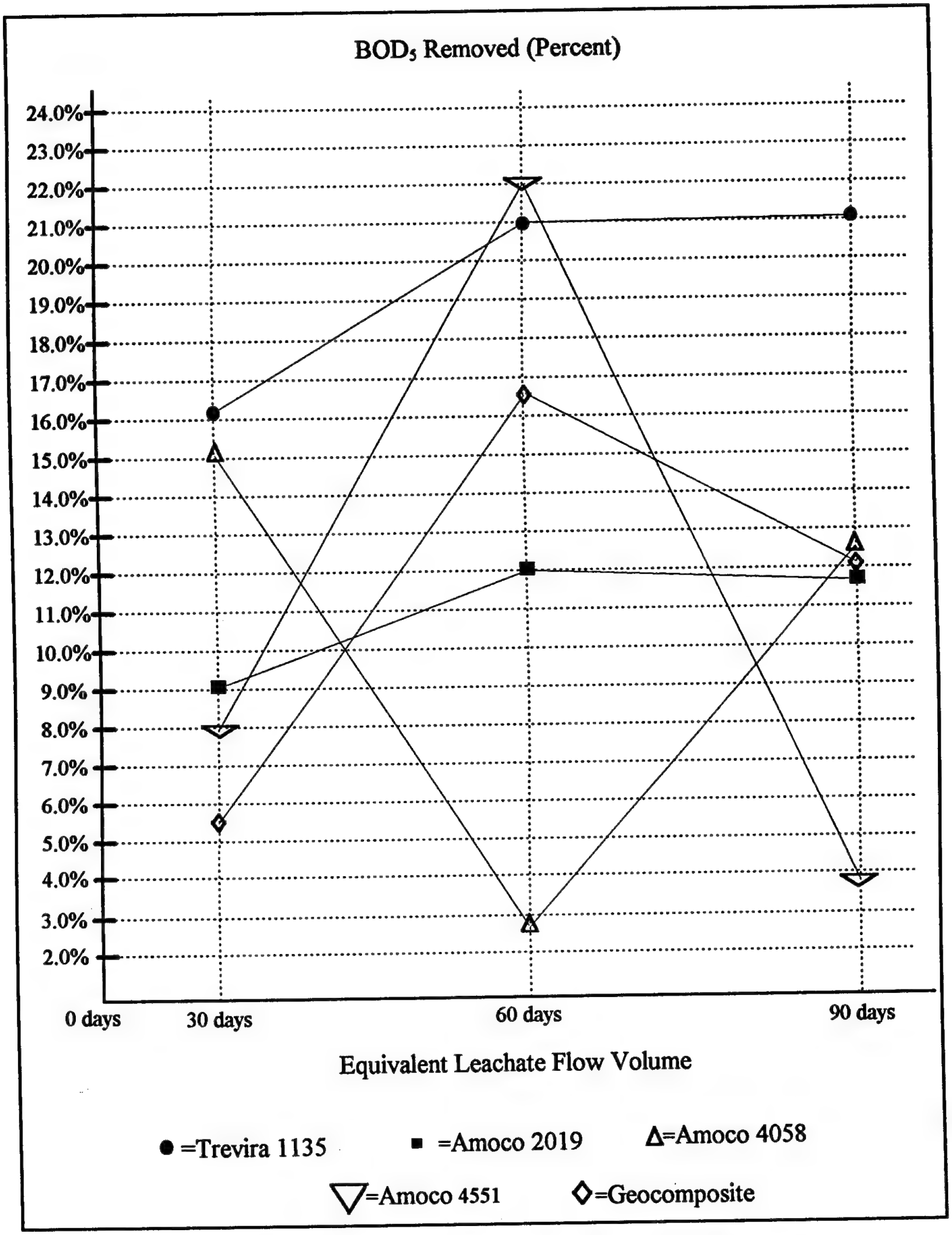


Figure 7.5: BOD_5 Removal Percentages for All Geotextiles

High Concentration Leachate Flow

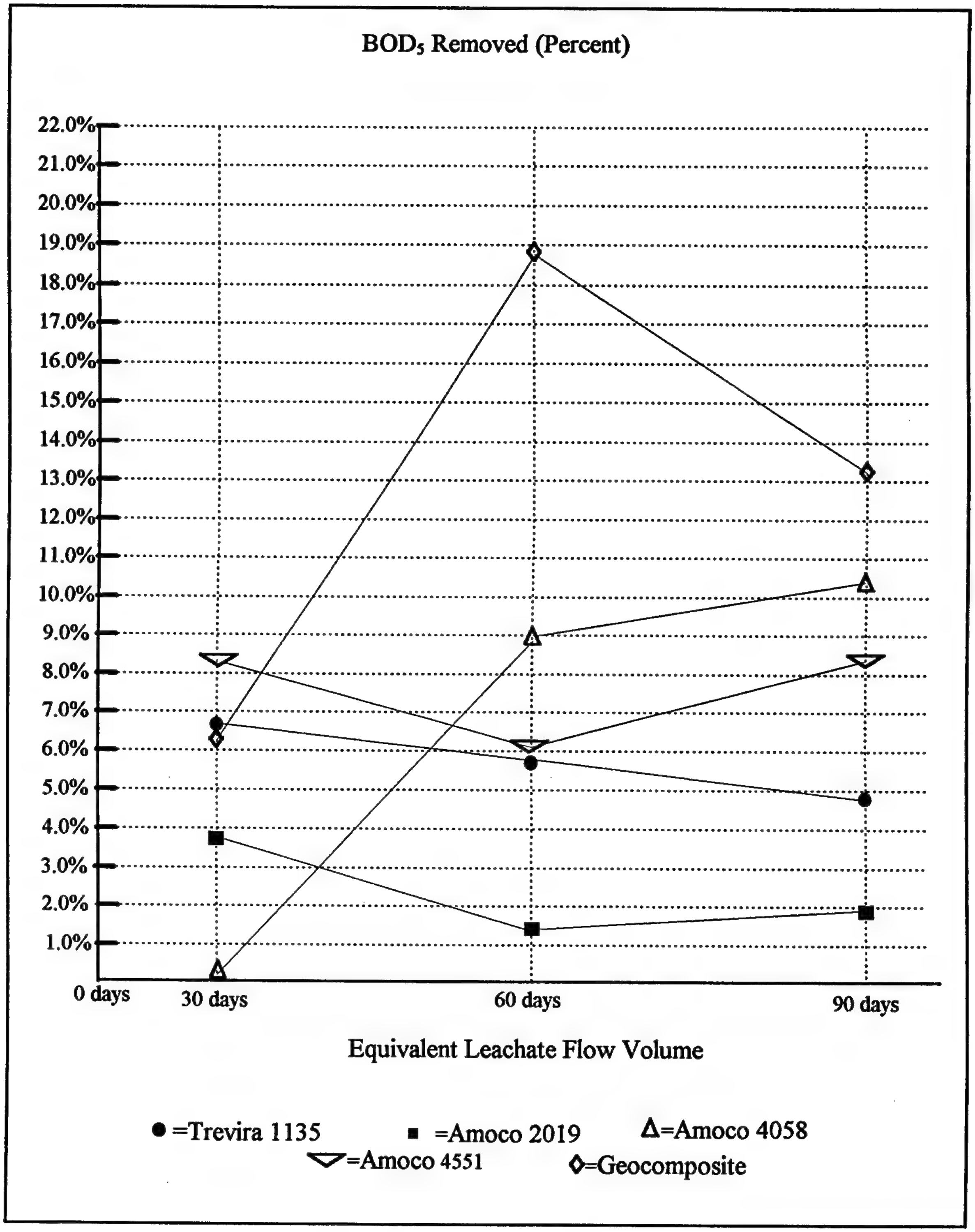


Figure 7.6: BOD$_5$ Removal Percentages for All Geotextiles

Low Concentration Leachate Flow

7.6 Chemical Oxygen Demand Removal

COD removal percentages were consistently higher than those for BOD_5 removal. Percentage removal rates are contained in Tables 7.10 and 7.11 and shown graphically in Figures 7.7 and 7.8. The geotextiles had a range of 27 to 39 percent removal over the ninety day time period for the high concentration leachate. This is with an initial average COD of the unfiltered leachate of around 40,100 mg/l. The low concentration leachates COD removal rates were lower ranging from 3 to about 19 percent. This is with an initial average COD value of 390 mg/l.

The t-test results comparing the remaining COD with that existing in the original leachate show that all geotextiles filtered a statistically significant amount of COD at all times under high concentration leachate flow. Under low concentration flow, the Trevira 1135 at all three flow volumes, the Geocomposite at 30 and 90 days, and the Amoco 4058 at a 90 day volume, filtered significant amounts of COD from the synthetic leachate. It was found also that at a high concentration, no geotextile statistically outperformed another in COD removal. This result was almost the same for low concentration flow where the only statistical difference was that the Geocomposite underperformed the other five samples after a 30 day volume of leachate.

Since the average COD removal at high concentrations was approximately 33% and at low concentration was approximately 15%, the question arises as to why COD is being filtered at more than double the rate in the high concentration leachate.

It is likely that the filter cake is acting as a COD filter itself. This will be addressed in Section 7.10.

Table 7.10: COD Removal Percentages for High Concentration Leachate

Geotextile	COD Removed - 30 Days (%)		Geotextile	COD Removed - 60 Days (%)		Geotextile	COD Removed -90 Days (%)	
Amoco 2019	38.2± 3.9		Amoco 2019	38.6± 9.0		Amoco 2019	35.2± 10.8	
Amoco 4551	32.9± 5.8		Amoco 4058	36.2± 4.0		Amoco 4058	34.6± 4.2	
Amoco 4058	33.4± 1.5	32.9	Geocomp	31.6± 5.6	33.7	Amoco 4551	33.6± 3.6	32.3
Geocomp	30.9± 8.6		Amoco 4551	31.2± 7.6		Trevira 1135	31.2± 6.6	
Trevira 1135	29.0± 7.6		Trevira 1135	31.0± 8.5		Geocomp	27.0± 13.2	

Table 7.11: COD Removal Percentages for Low Concentration Leachate

Geotextile	COD Removed - 30 Days (%)		Geotextile	COD Removed - 60 Days (%)		Geotextile	COD Removed - 90 Days (%)	
Amoco 4058	*15.5± 15.6*		Amoco 4551	*15.9± 10.3*		Trevira 1135	19.1± 3.7	
Trevira 1135	14.7± 4.2	13.5	Trevira 1135	15.5± 9.1		Geocomp	17.4± 7.7	
Amoco 2019	*13.4± 11.0*		Geocomp	14.2± 7.8	13.6	Amoco 4058	14.1± 10.8	15.1
Amoco 4551	*10.2± 9.8*		Amoco 4058	*11.4± 11.7*		Amoco 4551	*13.1± 18.9*	
Geocomp	*3.2± 8.2*		Amoco 2019	*11.2± 1.0*		Amoco 2019	*12.2± 11.6*	

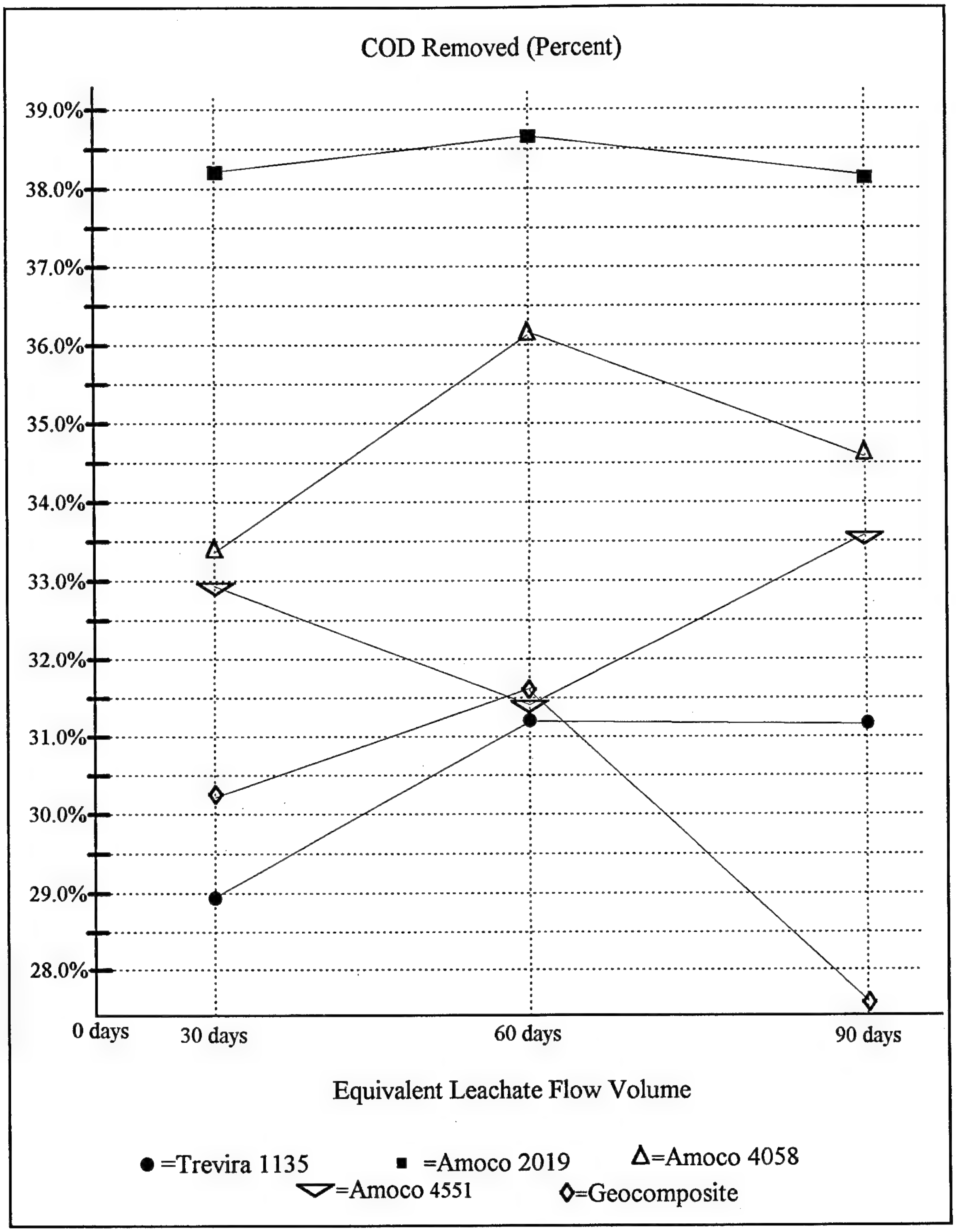


Figure 7.7: COD Removal Percentages for All Geotextiles

High Concentration Leachate Flow

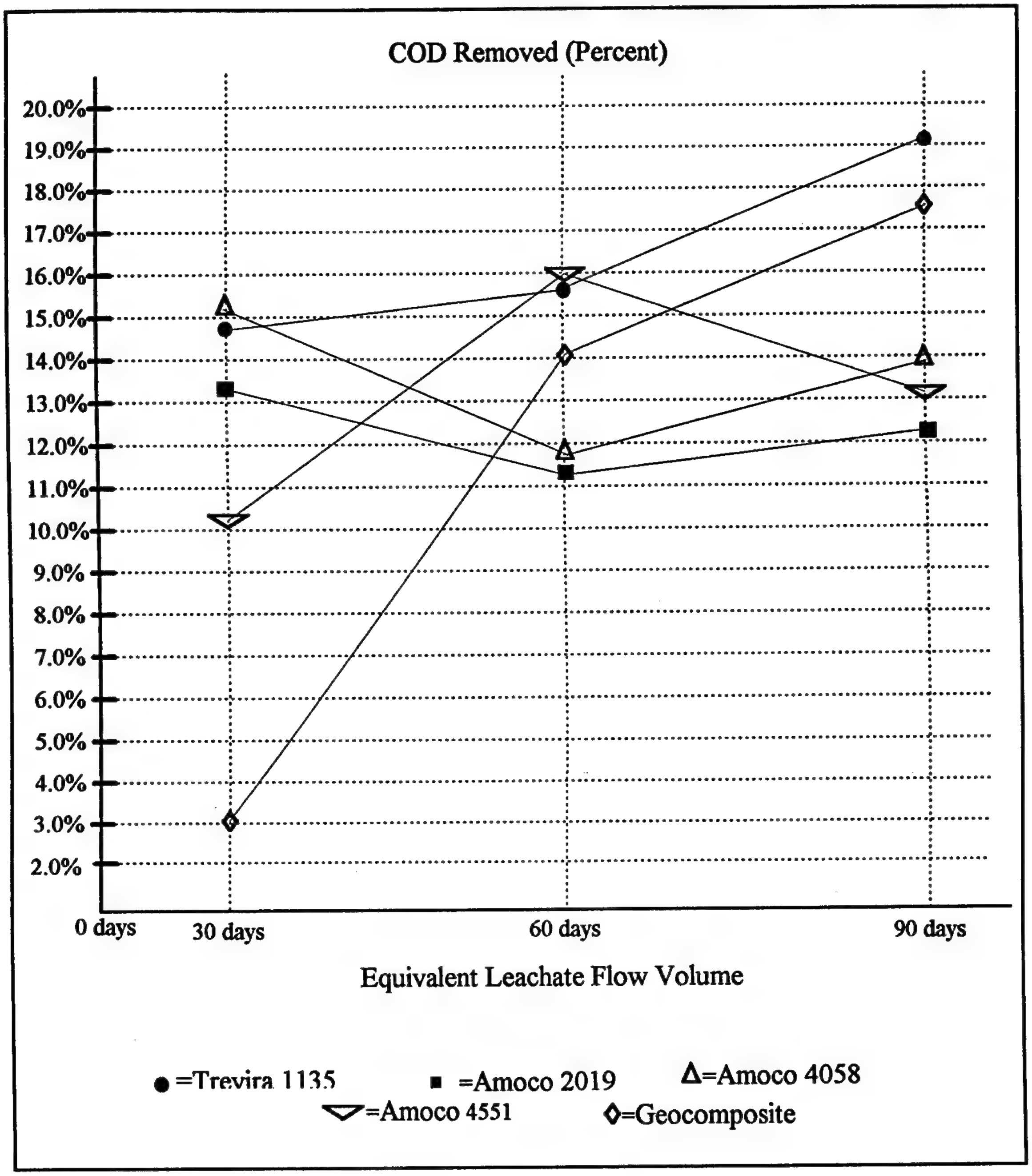


Figure 7.8: COD Removal Percentages for All Geotextiles

Low Concentration Leachate Flow

7.7 Total Suspended Solids Removal

The TSS removal rates were high particularly for the high concentration leachate. Percent removals are given in Tables 7.12 and 7.13. Graphs showing the percentage of removal are contained in Figures 7.9 and 7.10. All five geotextiles showed a higher than 99 percent removal rate for the high concentration leachate after 90 days. After 60 days, all but the Geocomposite showed greater than 90% removal rates. The Geocomposite did not show an increase in removal efficiency from 30 to 60 days. This is consistent with the permittivity data which decreased the least during this time frame and at this concentration. T - test results shown in Table 7.12 and 7.13 show that all geotextiles removed a statistically significant amount of TSS at all volumes and under both concentrations.

At high concentration, t-test results shown in Table 7.12 depict that the Amoco 4551 acts as the best TSS filter. At a 30 day volume, it ranks third but is statistically equal to the Trevira 1135 and the Geocomposite. At 30 and 90 day volumes, it filters statistically more than the other four samples. At 60 and 90 days, the Geocomposite underperforms all the other samples although at 90 days it is statistically equal to the Amoco 4058.

At low concentration, t-test results shown in Table 7.13 show that TSS removal rates are much less significant when comparing the geotextiles to each other. The Amoco 2019 is consistently outperformed by the others and this is statistically significant at all volumes except when comparing it to the Amoco 4058 at 60 days. At

30 and 60 day volumes three of the samples are statistically equal and at a 90 day volume four of the samples are statistically equal. Lastly it is important to note that at low concentration, the removal rate does not increase nearly as much as it does under high concentration flow.

7.12: TSS Removal Percentages for High Concentration Leachate

<table>
<tr><th>Geotextile</th><th colspan="2">TSS Removed - 30 Days (%)</th><th>Geotextile</th><th colspan="2">TSS Removed - 60 Days (%)</th><th>Geotextile</th><th colspan="2">TSS Removed - 90 Days (%)</th></tr>
<tr><td>Trevira 1135</td><td>61.7± 9.3</td><td rowspan="3">59.0</td><td>Amoco 4551</td><td colspan="2">98.8± 0.2</td><td>Amoco 4551</td><td colspan="2">99.63± 0.07</td></tr>
<tr><td>Geocomp</td><td>58.3± 7.7</td><td>Amoco 4058</td><td>98.3± 0.9</td><td rowspan="2">98.1</td><td>Trevira 1135</td><td>99.49± 0.02</td><td rowspan="2">99.45</td></tr>
<tr><td>Amoco 4551</td><td>57.1± 6.1</td><td>Amoco 2019</td><td>97.8± 0.5</td><td>Amoco 2019</td><td>99.4± 0.1</td></tr>
<tr><td>Amoco 4058</td><td colspan="2">53.3± 2.8</td><td>Trevira 1135</td><td colspan="2">91.5± 0.5</td><td>Amoco 4058</td><td>99.29± 0.06</td><td rowspan="2">99.2</td></tr>
<tr><td>Amoco 2019</td><td colspan="2">35.4± 10.3</td><td>Geocomp</td><td colspan="2">56.7± 4.0</td><td>Geocomp</td><td>99.1± 0.4</td></tr>
</table>

Table 7.13: TSS Removal Percentages for Low Concentration Leachate

Geotextile	TSS Removed - 30 Days (%)		Geotextile	TSS Removed - 60 Days (%)		Geotextile	TSS Removed - 90 Days (%)	
Amoco 4551	60.5± 2.1	56.4	Trevira 1135	43.7± 8.1	42.3	Amoco 4058	50.6± 5.4	48.7
Amoco 4058	54.5± 5.8		Geocomp	42.2± 1.1		Amoco 4551	50.1± 6.8	
Geocomp	54.2± 3.9		Amoco 4551	41.0± 8.0		Trevira 1135	48.1± 1.5	
Trevira 1135	49.4± 4.0		Amoco 4058	37.3± 9.8	33.8	Geocomp	45.8± 7.9	
Amoco 2019	23.6± 11.0		Amoco 2019	30.3± 6.7		Amoco 2019	31.1± 6.2	

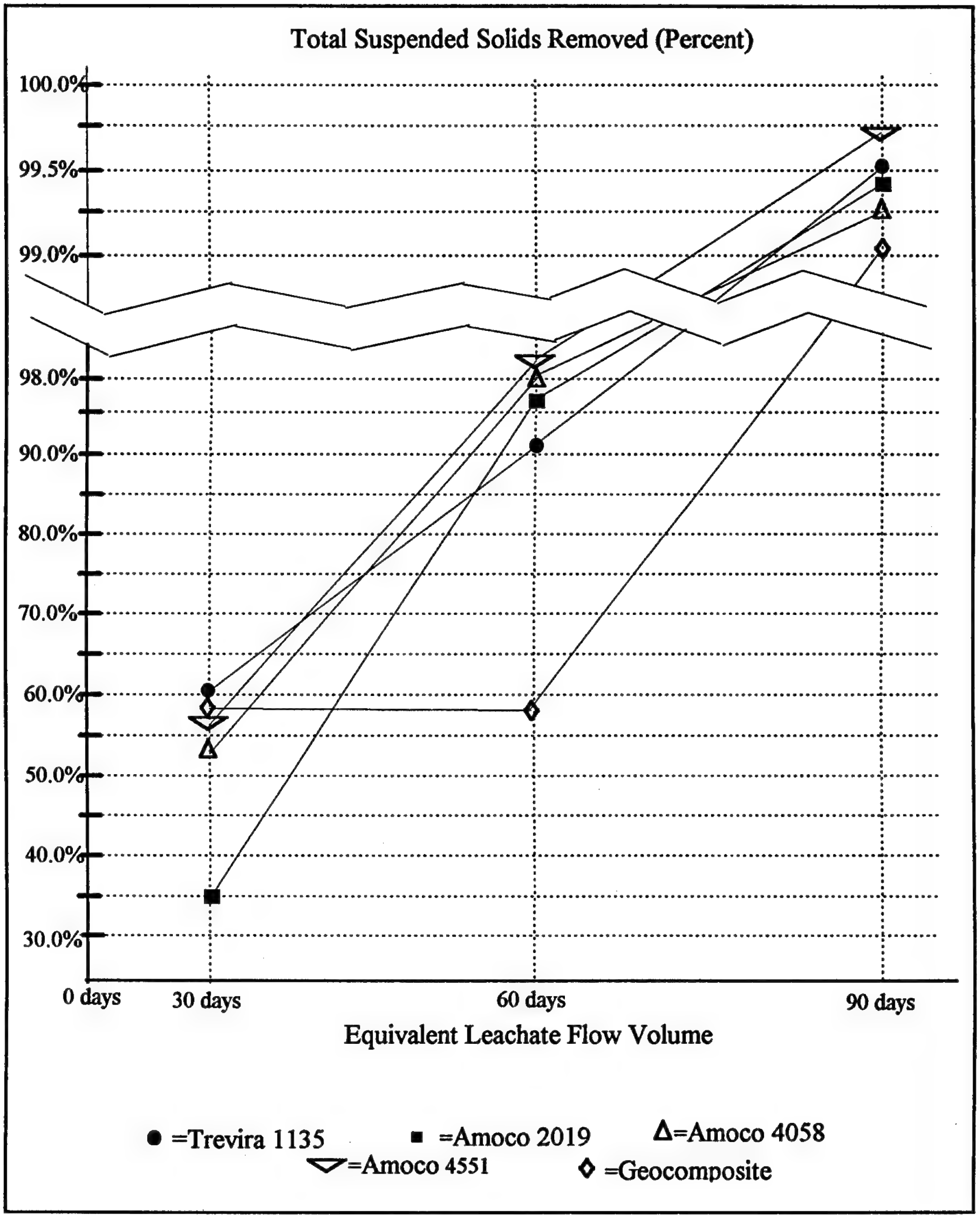


Figure 7.9: Total Suspended Solids Removal Percentages for All Geotextiles High Concentration Leachate Flow

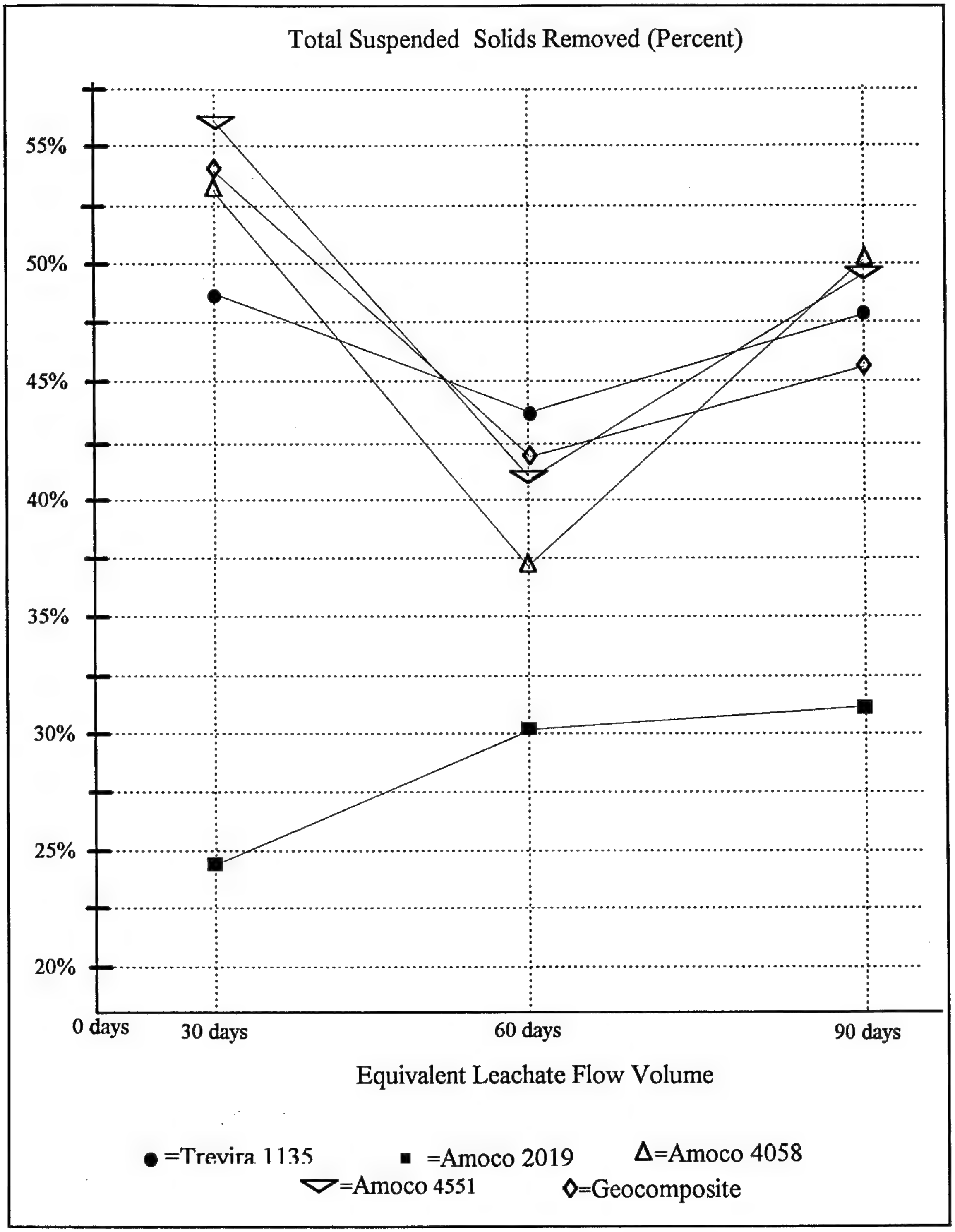


Figure 7.10: Total Suspended Solids Removal Percentages for All Geotextiles

Low Concentration Leachate Flow

7.8 Iron Removal Results

Iron removal percentages are shown in Table 7.14 for high concentration synthetic leachate and Table 7.15 for low concentration synthetic leachate. These results are also depicted in graphs in Figures 7.11 and 7.12. Although many of the removal percentages appear high, very few show iron removed in a statistically significant manner when comparing the filtered to the unfiltered leachate. T-test results comparing filtered and unfiltered leachate shown in the two tables reveals that at high concentration, at 30 days, no geotextile filtered a significant amount of iron. At 60 and 90 days, all except the Geocomposite were able to filter iron. At low concentration, no geotextile filtered any significant iron at any volume of leachate.

Comparing the geotextiles at low concentration, there are differences in the removal percentages, but none of these differences were statistically significant. With high concentration leachate, the Amoco 4551 and the Amoco 2019 outperformed the other three geotextiles at 60 days, and all but the Amoco 4058 at 90 days. The filters were all statistically equal after a 30 day volume of high concentration synthetic leachate.

This leads to the conclusion that after time the geotextiles will begin to filter iron. Iron removal will be addressed Section 7.10.

Table 7.14: Iron Removal Percentages for High Concentration Leachate

Geotextile	Iron Removed - 30 Days (%)		Geotextile	Iron Removed - 60 Days (%)		Geotextile	Iron Removed - 90 Days (%)	
Trevira 1135	*16.6± 8.3*		Amoco 4551	41.0± 2.5	40.6	Amoco 4551	46.0± 3.2	
Amoco 4551	*11.8± 7.9*		Amoco 2019	40.2± 3.1		Amoco 4058	42.3± 3.5	42.0
Amoco 2019	*11.5± 5.1*	10.0	Amoco 4058	35.5± 1.6		Amoco 2019	37.6± 3.4	
Geocomp	*5.2± 4.6*		Trevira 1135	23.3± 1.2	22.1	Geocomp	*26.2± 9.3*	26.0
Amoco 4058	*4.8± 3.6*		Geocomp	*21.0± 10.2*		Trevira 1135	25.8± 3.8	

Table 7.15: Iron Removal Percentages for Low Concentration Leachate

Geotextile	Iron Removed - 30 Days (%)		Geotextile	Iron Removed - 60 Days (%)		Geotextile	Iron Removed - 90 Days (%)	
Geocomp	*40.7± 6.7*		Geocomp	*39.0± 6.7*		Trevira 1135	*41.1± 3.5*	
Trevira 1135	*26.0± 3.5*		Trevira 1135	*34.8± 4.6*		Amoco 4058	*33.6± 6.3*	
Amoco 4058	*25.4± 11.1*	24.6	Amoco 4551	*24.9± 8.1*	28.2	Geocomp	*32.3± 12.5*	30.6
Amoco 4551	*24.3± 7.6*		Amoco 4058	*23.3± 11.9*		Amoco 4551	*28.4± 6.9*	
Amoco 2019	*6.8± 6.8*		Amoco 2019	*19.0± 4.7*		Amoco 2019	*14.6± 5.3*	

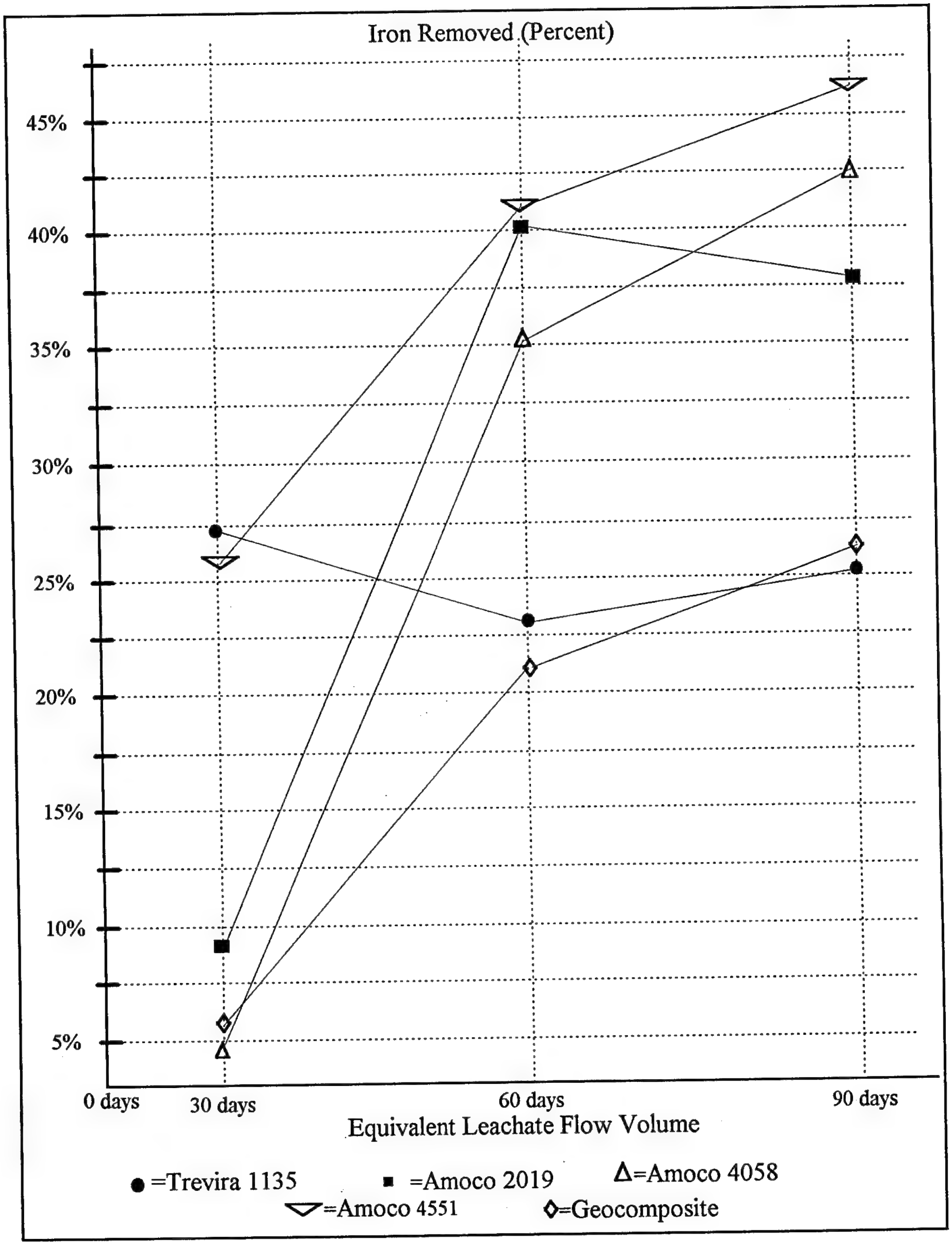


Figure 7.11: Iron Removal Percentages for All Geotextiles

High Concentration Leachate Flow

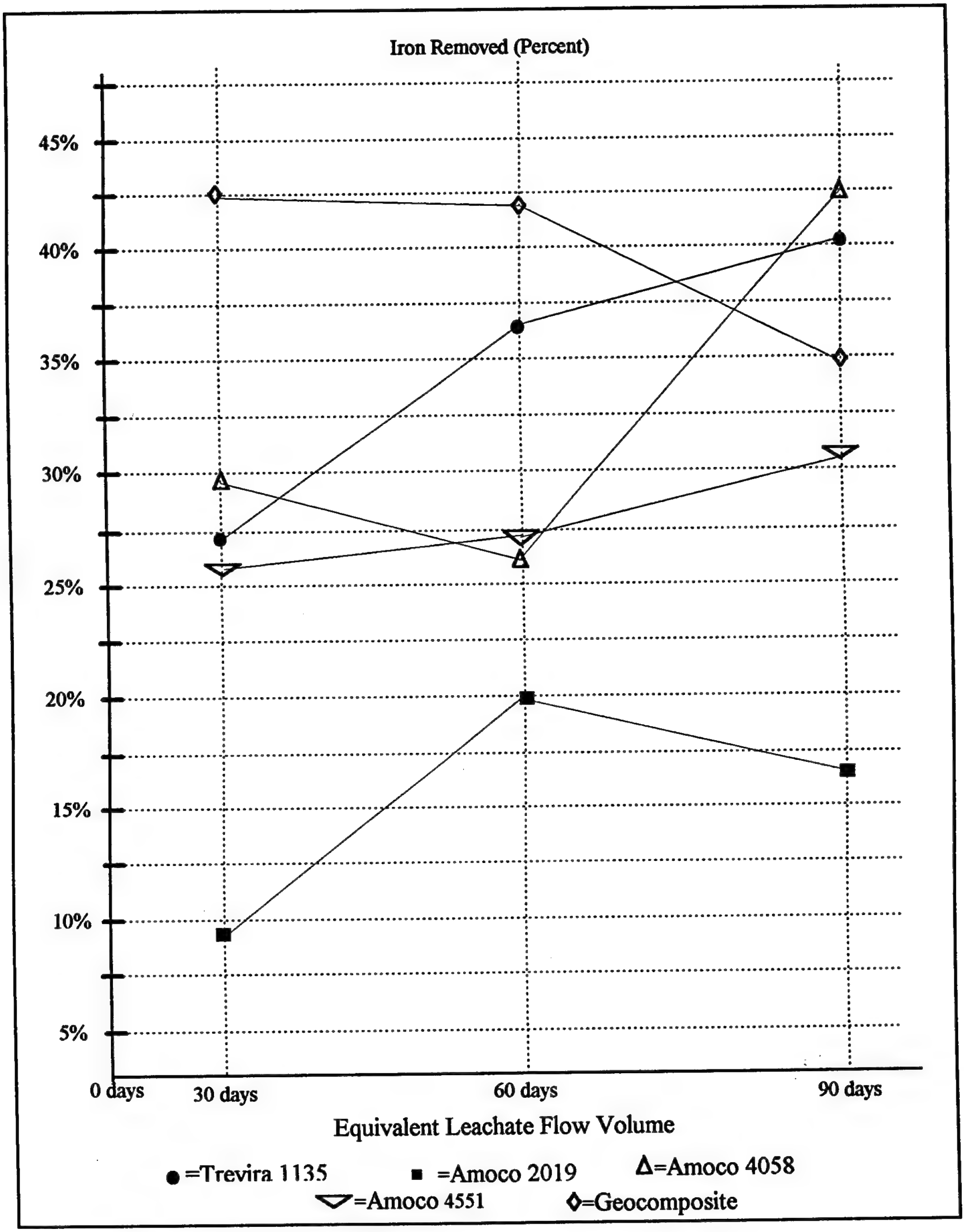


Figure 7.12: Iron Removal Percentages for All Geotextiles

Low Concentration Leachate Flow

7.9 Zinc Removal Results

Zinc removal rates are shown in Tables 7.16 and 7.17 for high and low concentration leachate and graphically in Figures 7.13 and 7.14. Zinc concentrations were inconsistent from test to test. Separate t-tests were performed on the five concentrations in each test for each data point versus the same data point in the other two tests. Results that were not statistically equal are shown with the individual results of the three tests and shaded darkly. Because the three tests are statistically unequal, they cannot be grouped together. The Amoco 4551 at a 60 day volume of high concentration flow is an example of this. The five removal rates obtained for it during test 1(36.8±5.8), 2(63.7±3.0), and 3 (12.3±4.8) were statistically unequal to each other and therefor not grouped together. The removal rates shaded darkly were all statistically significant, but not consistent. For the remainder, all data points were used to compute the overall mean and confidence interval.

At high concentration, the Amoco 2019 and Trevira 1135 were found to effectively filter zinc at all volumes. They were statistically equivalent at 30 and 60 day volumes, while at 90 days, the Trevira statistically outperformed the Amoco 2019. Their removal rates ranged from 16% to over 40 %. Data is available for the Amoco 4058, Geocomposite, and Amoco 4551 after a 30 day volume of flow. None of these showed any statistically significant ability to remove the zinc. The Amoco 4551, Geocomposite, and Amoco 4058 all showed inconsistent but significant removal rates at 60 and 90 day volumes.

At low concentration, the Amoco 4551 showed a statistically significant ability to filter zinc. Its removal rate ranged from 56% to 65% during the three volumes of flow. The Geocomposite at 60 and 90 day volumes and the Trevira 1135 at a 30 day volume also showed the ability to filter zinc from solid waste landfill leachate. The Amoco 2019 did not show the ability to filter a statistically significant amount of zinc at any volume. The Amoco 4058, the Geocomposite at a 30 day volume, and the Trevira 1135 at 60 and 90 day volumes showed inconsistent but significant removal.

Filtration of zinc may occur because the zinc is forming a percipitate. Figure 7.13 shows a log concentration curve for zinc ions. At a pH of 5.8, which was found in these tests, little zinc stays in solution. It is therefore likely that the geotextiles are filtering it out as a solid.

Table 7.16: Zinc Removal Percentages for High Concentration Leachate

Geotextile	Zinc Removed - 30 Days (%)		Geotextile	Zinc Removed - 60 Days (%)		Geotextile	Zinc Removed - 90 Days (%)
Amoco 2019	23.2± 7.1	20.7	Amoco 4551	36.8±5.8, 63.7±3.0, 12.3±4.8		Amoco 4551	25.4±5.9, 57.3±4.1, 11.7±3.6
Trevira 1135	18.1± 7.2		Amoco 2019	42.8± 4.6	39.9	Trevira 1135	28.1± 4.7
Amoco 4058	*12.4± 2.0*	10.2	Trevira 1135	37.4± 4.4		Amoco 2019	16.1± 4.7
Geocomp	*10.4± 4.0*		Geocomp	25.0±9.8, 64.3±4.5, 17.7±4.5		Geocomp	22.3±4.1, 13.3±3.6, 21.6±3.1
Amoco 4551	*7.8±*		Amoco 4058	*6.8±3.0*, 53.7±5.0, 22.0±3.1		Amoco 4058	*6.6±2.0*, 25.9±5.0, 15.5±4.2

Table 7.17: Zinc Removal Percentages for Low Concentration Leachate

Geotextile	Zinc Removed - 30 Days (%)	Geotextile	Zinc Removed - 60 Days (%)	Geotextile	Zinc Removed - 90 Days (%)
Amoco 4058	40.2±6.5, 97.0±1.1, 54.3±28.5	Trevira 1135	40.1±11.3,99.5±1.0, 70.3±16.8	Trevira 1135	30.3±8.0, *9.4±1.0*, 49.1±25.1
Amoco 4551	65.5± 13.0	Geocomp	74.1± 4.3	Amoco 4058	27.3±11.3,93.7±2.0, 54.3±16.9
Trevira 1135	65.5± 10.6	Amoco 4551	62.6± 8.0	Geocomp	65.2± 7.0
Geocomp	33.3±9.8,89.8±10.4, 39.0±8.9	Amoco 4058	37.9±8.8, 93.1±2.0, 38.4±31.6	Amoco 4551	56.3± 11.5
Amoco 2019	*28.2± 12.9*	Amoco 2019	*33.6± 14.2*	Amoco 2019	*41.2± 14.6*

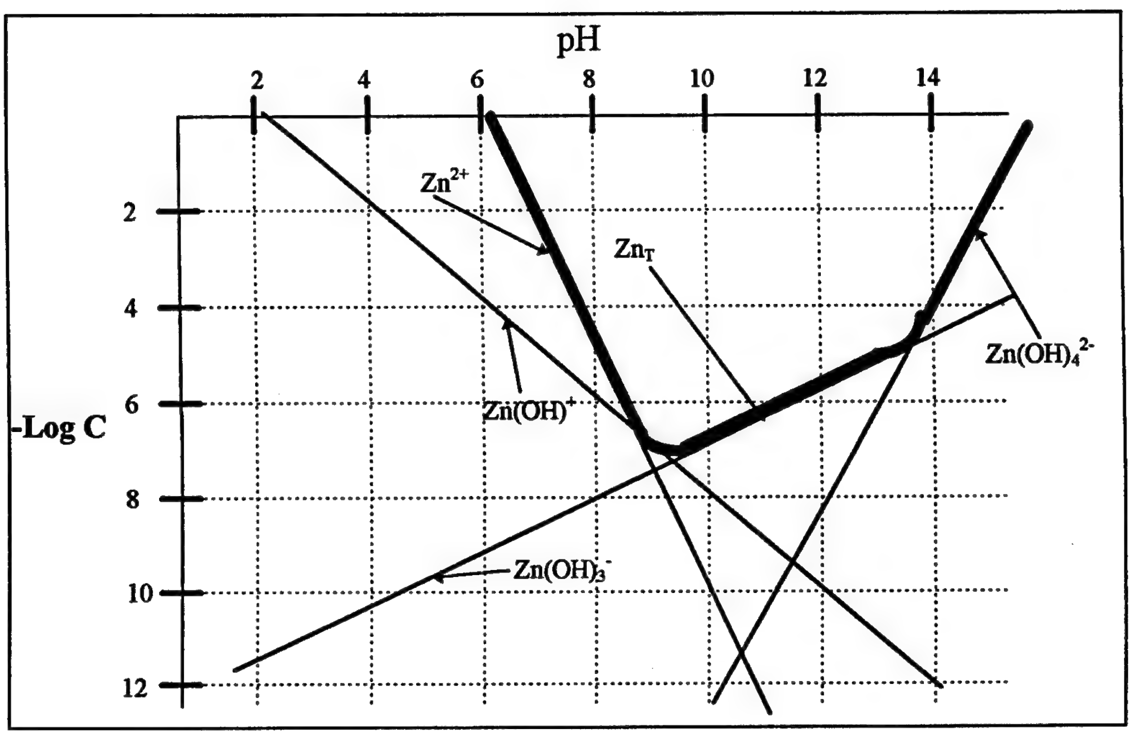


Figure 7.13: Solubity of Zinc; Log Concentration versus pH

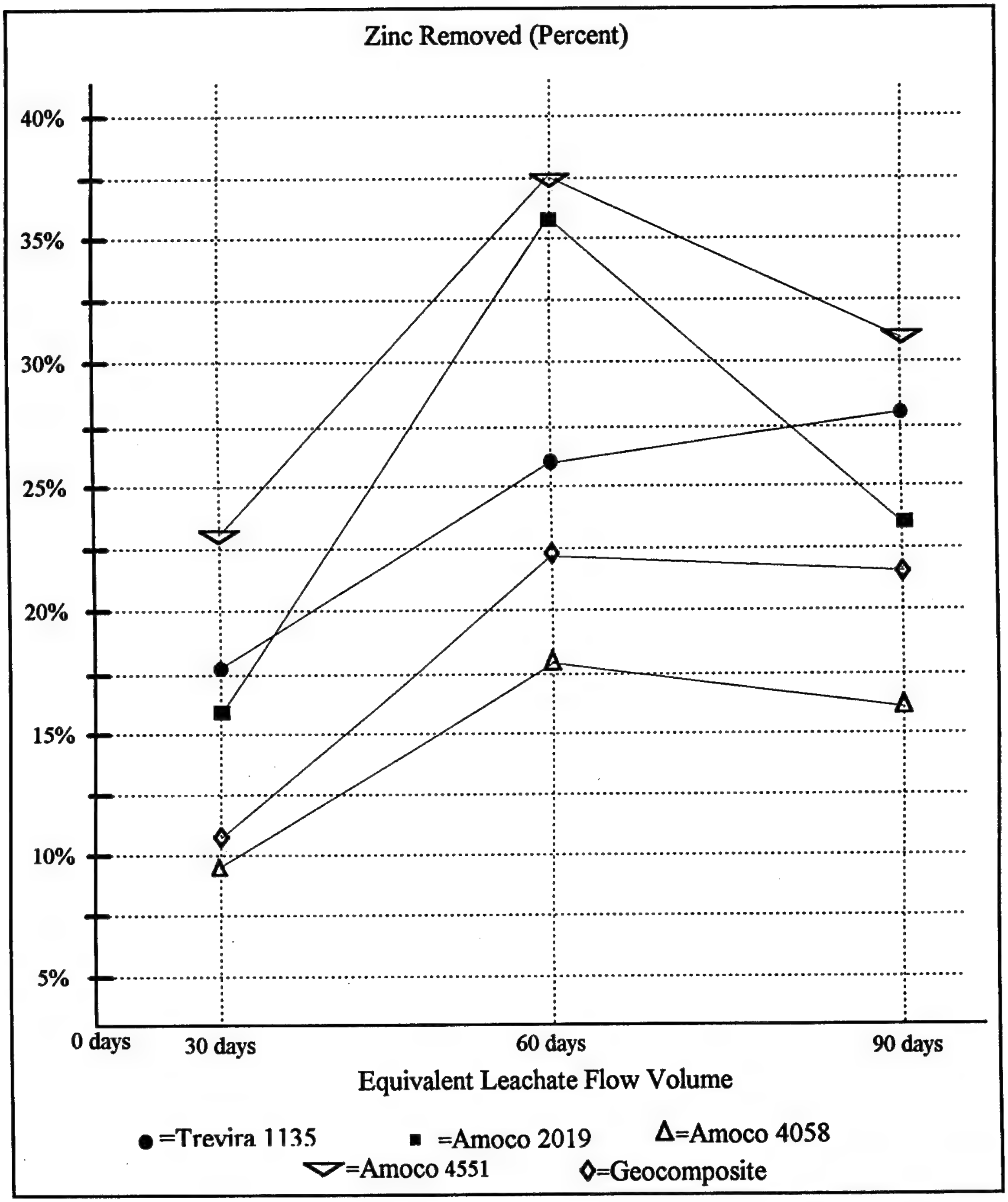


Figure 7.14: Zinc Removal Percentages for All Geotextiles

High Concentration Leachate Flow

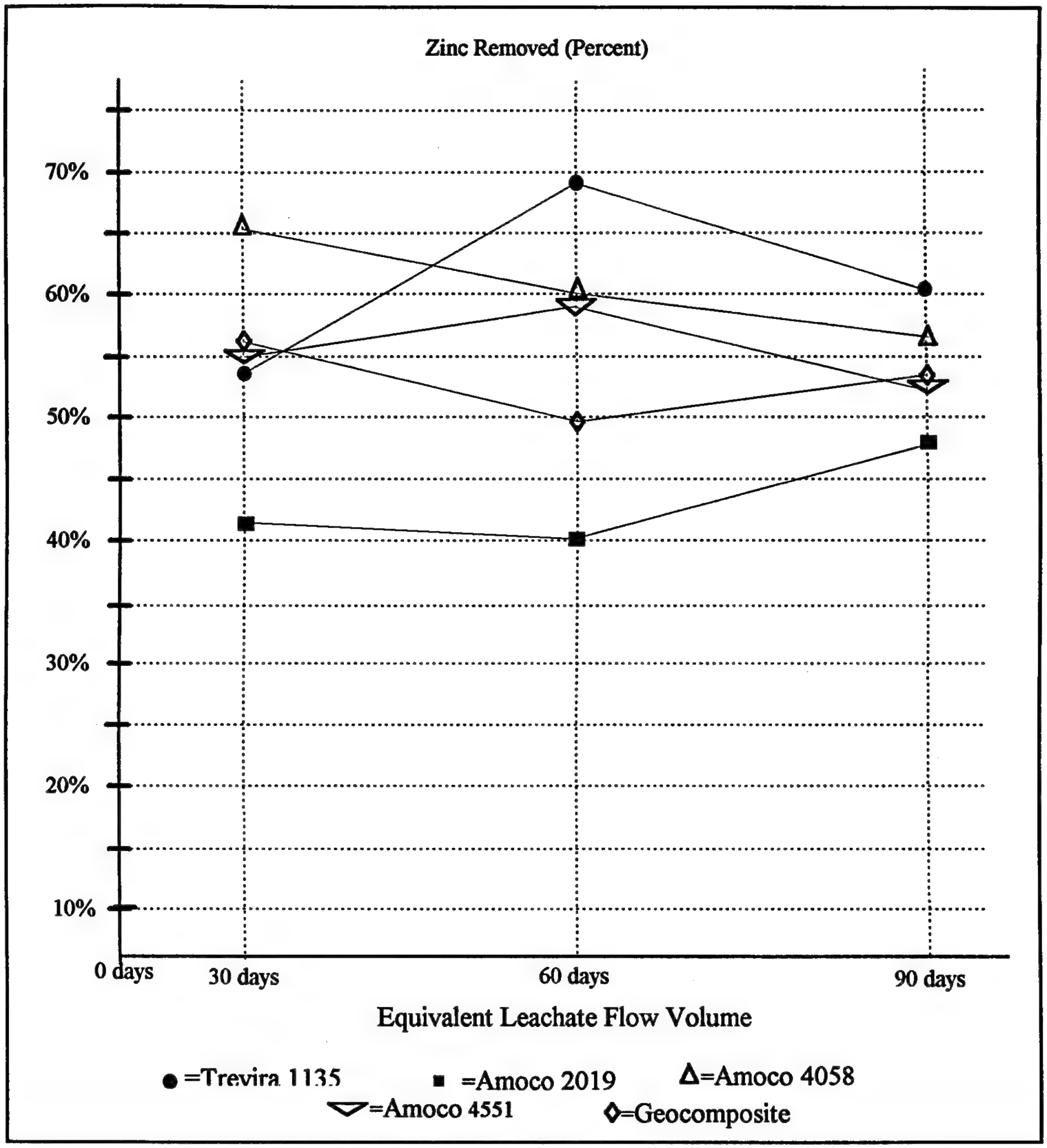


Figure 7.15: Zinc Removal Percentages for All Geotextiles

Under Low Concentration Leachate Flow

7.10 Filter Cake Analysis

As noted in the COD (7.6) and the Iron section (7.8), these two constituents are being removed by the geotextiles at a higher removal rate in the high concentration leachate. Approximately 30% of the COD in the high concentration leachate is removed while approximately 15% in the low concentration leachate. Similarly, iron removal rates are higher in the high concentration leachate as a greater volume of leachate passes through this sample. This was investigated to determine if the filter cake that appears on the geotextile is the cause of these higher removals. After high concentration leachate is filtered, a large filter cake forms, while the low concentration filter cake is much less apparent. This difference is depicted in the photographs in Figure 7.4. Because of the large difference in filter cakes, it is suggested in this study, that it is the cause of the additional filtration of COD and Iron that occurs in high concentration leachate.

In order to determine if the geotextiles or the filter cake were causing this increased filtration, high concentration leachate was again mixed. It was done exactly as depicted in Chapter 6 except that no colloidal kaolin was added. This resulted in a filter cake less apparent than those achieved in low concentration testing. Three 30 day volumes were mixed and filtered through the Amoco 4551. The unfiltered and the filtered leachate were then tested for COD and iron and removal rates determined. Results of these tests are contained in Appendix F. A comparison of the results are shown in Table 7.18 for COD and 7.19 for iron. T-tests results are depicted in these

tables. Removal rates that were found to be statistically equal are shaded. They show that the removal rates of COD and iron in the leachate with no colloidal kaolin were statistically equal to those obtained for low concentration leachate, and in some cases were lower. The same result occurred with iron removal except that the iron removal rate was statistically equal to high concentration leachate at a 30 day volume.

Table 7.18: Filter Cake COD Removal Analysis

Results of Amoco 4551

Volume	High Concentration COD Removal (%)	Low Concentration COD Removal (%)	High Conc w/o Colloidal Kaolin COD Removal (%)
30 Days	32.9 ± 5.8	10.2 ± 9.8	4.5 ± 14.3
60 Days	31.2 ±7.6	15.9 ± 10.3	12.7 ± 16.2
90 Days	33.6 ±3.6	13.1 ± 18.9	8.2 ± 15.9

Table 7.19: Filter Cake Iron Removal Analysis

Results of Amoco 4551

Volume	High Concentration Iron Removal (%)	Low Concentration Iron Removal (%)	High Conc w/o Colloidal Kaolin Iron Removal (%)
30 Days	11.8 ± 7.9	24.3 ± 7.6	7.4 ± 10.1
60 Days	41.0 ± 2.5	24.9 ± 8.1	13.7 ± 7.8
90 Days	46.0 ± 3.2	28.4 ± 6.9	8.7 ± 8.0

The results of this test leads to two possible explanations for the additional filtration of COD and iron in leachate with a high concentration of TSS:

1. That the clay is forming a large filter cake and is filtering the additional COD and iron. This seems unlikely for the COD because the organic acids in the leachate are dissolved and should stay in the solution and pass through the filter cake and geotextile. It is likely that the filter cake is responsible for the additional iron removal . Leachate pH values were measured to be approximately 5.8 and this is consistant with the studies shown in Table 3.2. The concentration of Iron added to high concentration leachate equates to approximately a $2x10^{-2}$ M solution of Iron. At this concentration and pH, a large percent of the iron would be expected to percipitate out a $Fe(OH)_{3(s)}$ (see log solubility plot in Figure7.15). This percipitate is likely to be filtered by the filter cake and geotextile.

2. That there is an adsorption process occuring in the leachate before it reaches the geotextile. Clay particles typically have a negative surface charge and large surface areas. Acetic Acid has a pKa value of 4.75. At a pH of 5.8, approximately 10% will stay in the form, HAc with a neutral charge, therefore it is possible that 10% are becoming attached to the surfaces of the clay particles. The remainder in the form Ac^- would repel the surface of the clay particles. This may be a situation that only occurs when colloidal kaolin is used. Other, larger soil particles will have much less surface and therefore less likelihood of this adsorption process occurring. The metals may be also be undergoing adsorption but this is unlikely to be responsible for the major change in iron concentration seen. As shown in Figure 7.15,

the concentration of positively charged iron is very low at pHs around 5.8 and therefore little adsorption would be expected.

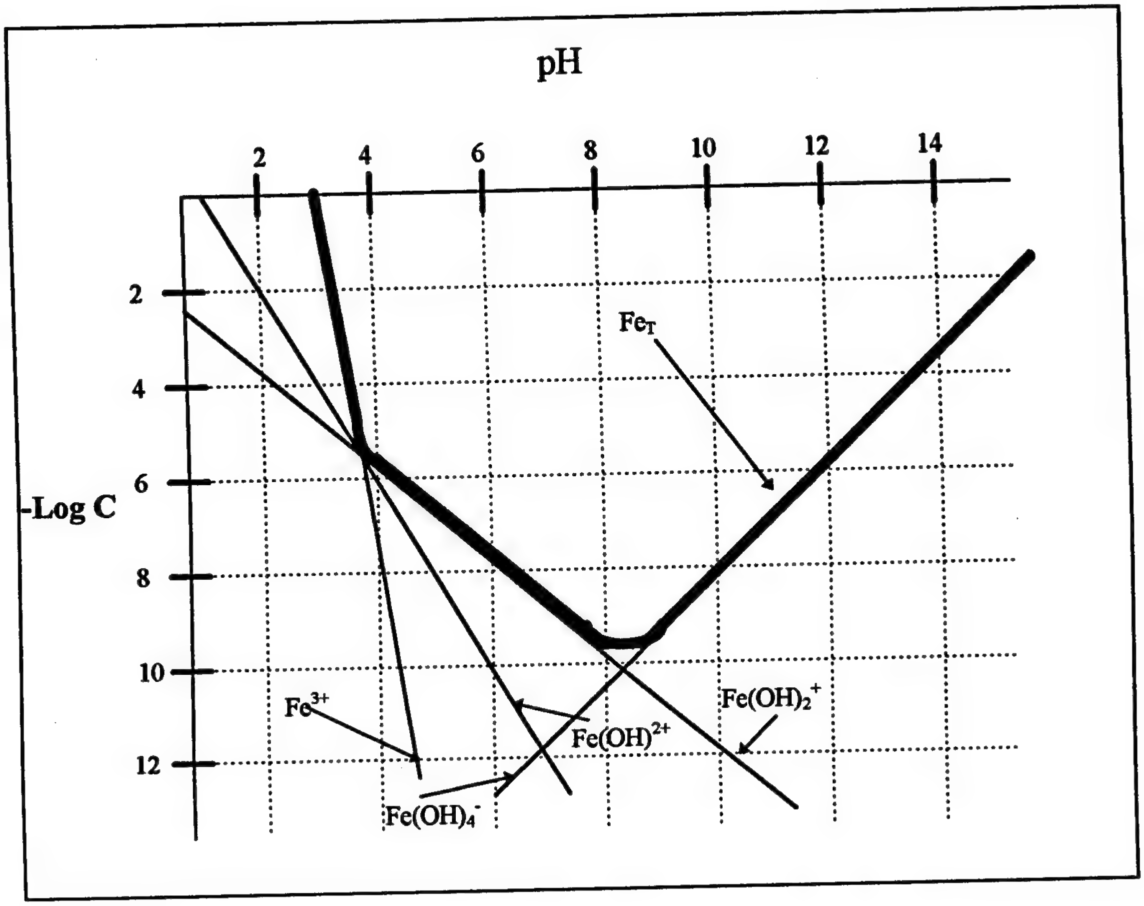


Figure 7.16: Solubility of Iron; Log Concentration versus pH

CHAPTER 8 - CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The following were stated objectives of this research and conclusions based on this research for each objective:

1. Determine if there is a statistically significant change in the concentration of various contaminants in leachate as it passes through the Geotextile. Synthetic leachate were filtered through five products to determine if there were significant changes in the BOD, COD, TSS, iron, and zinc concentrations. It was found that:

a. At no time was BOD removal found to be statistically significant in low concentration landfill leachate. In high concentration leachate, BOD filtration was found to be statistically significant in one geotextile (the Trevira 1135) during the testing period. The others did not consistently remove BOD.

b. Approximately 30% of the COD demand was filtered by the geotextiles during high concentration leachate testing. This was found to be statistically significant for all geotextiles and the reduction was constant throughout the three testing volumes. At lower concentrations, the removal percentage is lower and not always statistically significant. The geotextiles removed approximately 14%

of the COD from the low concentration leachate and this remained relatively constant throughout testing. The filter cake appears to be related to the increased COD removal seen in high concentration leachate.

c. TSS removal is always significant when filtering solid waste landfill leachate through a geotextile. All of the tested geotextiles begin filtering significant amounts of suspended solid immediately after flow is initiated. Removal rates eventually exceed 99% for these geotextiles that are used as filters under high concentration leachate conditions. Under low concentration flow conditions, the removal rate remains approximately 50%. An increase in the removal rate was not seen in the geotextiles as low concentration leachate passes through.

d. Iron removal rates are significant only under high concentration flow conditions and only for particular geotextiles after a 60 day volume of leachate passes. The filter cake that forms on the geotextile appears to cause the actual filtration of the iron under these conditions and not the geotextile itself. Under low concentration leachate flow, iron is not removed in a significant amount.

e. Zinc removal was found to be significant for some geotextiles at both high and low concentration leachate flow. The results of these tests were not conclusive for several geotextiles ability to filter zinc. Further testing, to obtain more

data points would be required to determine if zinc is being filtered. Other geotextiles showed no ability to filter zinc from solid waste landfill leachate.

2. Test permittivity of samples and generally correlate them the results obtained in a study done by Koerner at the GRI. The permittivity of geotextiles decreases with increased leachate volumes and under increased contaminant concentrations. At high concentrations, the geotextile permittivity dropped to approximately $6x10^{-6}$ sec^{-1} after a 90 day volume of flow. At low concentrations, the permittivities will decrease also, but at a much slower rate. Although slightly lower permeability was seen in this study than in the Koerner study, for like products after equal amounts of TSS loads were applied, permeabilities (and hence permittivities) were similar.

3. Test the use of a geocomposite to determine if it might be more effective as a solid waste landfill leachate filter. The geocomposite GT-80AP was tested to determine if it is a more effective. It maintained significantly higher permittivity after a 30 day volume of high concentration leachate flow than the other samples. The difference was not significant after 60 and 90 days of leachate flow. The geocomposite removed the smallest amount of TSS after a 60 day volume of high concentration leachate flow. Other results showed that statistically, the geocomposite did not statistically outperform or underperform the other tested sample.

8.2 Comparison of the Tested Geotextile Products

Tables 8.1 and 8.2 summarize the performance ranking of the five tested products during these experiments. Table 8.1 summarizes them under high concentration landfill leachate flow conditions and Table 8.2 summarizes them under low flow concentration conditions. Each geotextile is ranked in order with the sample that performed the most favorably on top and the least favorably on the bottom. Samples that did not show statistically significant performance differences are grouped together. Geotextiles that removed zinc inconsistently are in black.

When a landfill designer needs to choose between geotextiles, he can use the data in this report to help determine contaminant removal potential of these geotextiles, as well as predict the caused by the leachate on the permittivity of the geotextile. Although this gives the landfill designer a base to help choose a geotextile, a site specific approach which tests the geotextile in conjunction with the actual waste, anticipated flow rate, and local soil conditions is still desirable.

Based on Tables 8.1 and 8.2 it is clear that no geotextile outperformed any other on a consistent basis. Specific conclusions based on comparing the tested samples in this study include:

1. That there is little difference between these samples with regard to removal efficiencies of BOD_5 and COD. BOD_5 will not be removed in statistically significant quantities, and COD is not dependent for the most part on which geotextile is chosen.

2. That the Geocomposite is the best product to use under high concentration leachate flow conditions. This is because it maintains the most permittivity after 20 days of flow. After 60 and 90 day volumes of flow, there is no statistically significant difference in the geotextiles under high concentration flow conditions. If high concentrations of TSS are present in a waste, then the Amoco 4551 may be the best product. This is because it filtered the greatest quantity of TSS and therefore would be the most likely to prevent the LCS from becoming clogged.

3. At low concentrations, the Trevira 1135 maintained significantly better permittivity throughout the testing. Under low flow conditions, it performed all filtration functions as well or better than the other samples except TSS removal at 30 days by the Amoco 4551, Amoco 4058, and geocomposite. It is the best product available of the five tested for low concentration flow conditions.

4. The Amoco 2019 is the least desirable of all the products tested. It consistently had the lowest permittivity and this was significant at all volumes under low concentration leachate flow conditions. It also performed many of the removal functions poorly and this was statistically significant in many cases.

Table 8.1: Comparison of Geotextile Performance - High Concentration

30 Day Volume

Permittivity	BOD_5 Removed	COD Removed	TSS Removed	Iron Removed	Zinc Removed
Geocomp	Trevira 1135	Amoco 2019	Trevira 1135	Trevira 1135	Amoco 2019
Amoco 4551	Amoco 4058	Amoco 4551	Geocomp	Amoco 4551	Trevira 1135
Amoco 4058	Amoco 2019	Amoco 4058	Amoco 4551	Amoco 2019	Amoco 4058
Trevira 1135	Amoco 4551	Geocomp	Amoco 4058	Geocomp	Geocomp
Amoco 2019	Geocomp	Trevira 1135	Amoco 2019	Amoco 4058	Amoco 4551

60 Day Volume

Permittivity	BOD_5 Removed	COD Removed	TSS Removed	Iron Removed	Zinc Removed
Geocomp	Amoco 4551	Amoco 2019	Amoco 4551	Amoco 4551	Amoco 4551
Amoco 4551	Trevira 1135	Amoco 4058	Amoco 4058	Amoco 2019	Amoco 2019
Trevira 1135	Geocomp	Geocomp	Amoco 2019	Amoco 4058	Trevira 1135
Amoco 4058	Amoco 2019	Amoco 4551	Trevira 1135	Trevira 1135	Geocomp
Amoco 2019	Amoco 4058	Trevira 1135	Geocomp	Geocomp	Amoco 4058

90 Day Volume

Permittivity	BOD_5 Removed	COD Removed	TSS Removed	Iron Removed	Zinc Removed
Geocomp	Trevira 1135	Amoco 2019	Amoco 4551	Amoco 4551	Amoco 4551
Amoco 4058	Amoco 4058	Amoco 4058	Trevira 1135	Amoco 4058	Trevira 1135
Amoco 4551	Geocomp	Amoco 4551	Amoco 2019	Amoco 2019	Amoco 2019
Trevira 1135	Amoco 2019	Trevira 1135	Amoco 4058	Geocomp	Geocomp
Amoco 2019	Amoco 4551	Geocomp	Geocomp	Trevira 1135	Amoco 4058

Table 8.2: Comparison of Geotextile Performance - Low Concentration

30 Day Volume

Permittivity	BOD$_5$ Removed	COD Removed	TSS Removed	Iron Removed	Zinc Removed
Trevira 1135	Amoco 4551	Amoco 4058	Amoco 4551	Geocomp	Amoco 4058
Geocomp	Trevira 1135	Trevira 1135	Amoco 4058	Trevira 1135	Amoco 4551
Amoco 4551	Geocomp	Amoco 2019	Geocomp	Amoco 4058	Trevira 1135
Amoco 4058	Amoco 2019	Amoco 4551	Trevira 1135	Amoco 4551	Geocomp
Amoco 2019	Amoco 4058	Geocomp	Amoco 2019	Amoco 2019	Amoco 2019

60 Day Volume

Permittivity	BOD$_5$ Removed	COD Removed	TSS Removed	Iron Removed	Zinc Removed
Trevira 1135	Geocomp	Amoco 4551	Trevira 1135	Geocomp	Trevira 1135
Geocomp	Amoco 4058	Trevira 1135	Geocomp	Trevira 1135	Geocomp
Amoco 4551	Amoco 4551	Geocomp	Amoco 4551	Amoco 4551	Amoco 4551
Amoco 4058	Trevira 1135	Amoco 4058	Amoco 4058	Amoco 4058	Amoco 4058
Amoco 2019	Amoco 2019	Amoco 2019	Amoco 2019	Amoco 2019	Amoco 2019

90 Day Volume

Permittivity	BOD$_5$ Removed	COD Removed	TSS Removed	Iron Removed	Zinc Removed
Trevira 1135	Geocomp	Trevira 1135	Amoco 4058	Trevira 1135	Trevira 1135
Geocomp	Amoco 4058	Geocomp	Amoco 4551	Amoco 4058	Amoco 4058
Amoco 4551	Amoco 4551	Amoco 4058	Trevira 1135	Geocomp	Geocomp
Amoco 4058	Trevira 1135	Amoco 4551	Geocomp	Amoco 4551	Amoco 4551
Amoco 2019	Amoco 2019	Amoco 2019	Amoco 2019	Amoco 2019	Amoco 2019

8.3 Limitations of this Research

Although this research gives removal rates, shows permittivity changes, and compares five separate products, there are limitations that the designer should consider when using this research to determine what landfill leachate filter to use at a site. Some of the important limitations include:

1. This research only considered one flow rate. The rate of 5000 liters/hr/ha is a rate that could be expected in a relatively wet climate before a cap is installed. The designer must design for a site specific flow rate.

2. This research considered only a flow volume that would be expected over a 90 day period. Landfills are typically open for a number of years and groundwater monitoring takes place for an even longer period. Although this must be considered, research done by Ragle (1995) has shown that the contaminant levels in leachate decrease over time.

3. Only two leachate concentrations were considered in this research one with very high and one with very low contaminant levels. It is unlikely that an actual landfill will have the exact level of contaminants that were tested here. The designer could, however use the information to extrapolate what filtration will occur. For instance, he could plot the original concentrations in the two leachates in this test

against the removal percent. Then taking the concentration from a particular site, determine an anticipated removal rate. This would assume that the removal rate is linear based on contaminant concentration.

4. Although the geotextiles used in this research give a broad sampling of the products used for this purpose, it is only a small segment of the products available for use a landfill leachate filter. Only one geocomposite was used, and there are an infinite possible number of combinations the designer could use for this purpose.

8.4 Recommendations for Further Research

As stated here and by Koerner in the Geosynthetic Research Institute Study, the importance of testing site specific conditions are critical to properly designing a geotextile used as a leachate filter. This study gives some basic estimates that the designer can use to determine how much BOD_5, COD, TSS, iron, and zinc will be removed from the solid waste landfill leachate, but site specific conditions should be determined to give specific answers. Based on this, some recommendations are made for further research:

1. That leachates with medium values for the tested constituents be tested. For instance, COD at only 40,000 and 400 mg/l was filtered through the samples. In order to determine if removal rates are in fact linearly dependent on concentration,

additional concentrations such as 1,000, 10,000 , and 20,000 mg/l might help confirm or deny this linearity. This will give better indications over a broader spectrum of possibilities of the removal rates are effected by concentration.

2. That actual leachates from landfills be used. This will give a better site specific approach to the constituent removals.

3. More geocomposites should be tested. This research found that the Geocomposite maintained more permittivity at high concentrations after a 30 day volume of flow, but did not generally act as a more effective filter. Testing more of these products would help determine their viability for this purpose.

4. The geotextiles should be tested over greater times. Ninety days is a good indication of how the geotextiles will behave in the short term but more time is needed to determine their behavior in the long-term. This is important because landfill life is measured in decades when considering the length of post closure groundwater monitoring.

5. More research is needed to determine why high and low concentration leachate removal efficiencies for COD and iron removal are different. In section 7.10, it was suggested that either the clay filtration cake or an adsoption process was

responsible for this phenomenon. Several tests should be conducted to see which is actually causing the effect. They include:

a. Test a soil other than clay (substitute for the TSS), with a much smaller surface area and compare the removal rates in high concentration leachate. If the COD and/or iron removal rates went down, this would be a strong indication that they are adsorbing on the clay and this action is responsible for the additional COD and/or iron removal. If the removal rates remain equal, adsorption is unlikely to be the cause because the removal rate would be surface area independent. This information would determine if removal rates were strongly dependent on suspended solids type. Since every landfill will probably have different particle size distributions in their TSS loads, removal rates would be expected to change from landfill to landfill.

b. Filtration of a large volume of high concentration leachate with no TSS load (maintaining the high concentration of other contaminants) after filtering a ninety day volume of high concentration leachate with TSS as used in this study. If adsorption is occurring (which is what is being tested) the removal rate of COD and/or iron should decrease with time because eventually all adsorption sites on the clay will be occupied. The behavior would be similar to the breakthrough curve for an adsorption column.

c. Test a much larger leachate volume. If COD and iron are actually being removed by the filter cake, then it would be expected that eventually the removal rate of these two would increase. This could also be done by filtering a leachate with only a high TSS load, followed by filtration of a high concentration leachate (as used in this research) and seeing if the removal rate for COD and/or iron increased. If the filter cake is actually removing either of these two, it would be expected that the removal rate would be higher in this new test because a larger filter cake exists at the beginning of the test.

REFERENCES

GENERAL REFERENCES

Adolophe, D., M. Lopes, and D. Sigli. "Experimental Study of Flow Through Geotextiles." *Textile Research Journal* **64**(1994):176-182.

Ahmed, S., R. Khanbilvardi, J. Fillos, and P. Gleason. "Two-Dimensional Leachate Estimation Through Landfills." *Journal of Hydraulic Engineering* **118**(1992): 306-322.

Air and Waste Management Association. "Maine Town Bucks Tradition in Landfill Capping Project." *Journal of Air and Waste Management Association* **42**(1992): 419-420.

American Society For Testing and Materials. *Annual Book of ASTM Standards: Construction, Section 4, Volume 04.08.* Philadelphia, Pennsylvania: ASTM, 1994.

American Society for Testing and Materials. "New Standards Address Design and Construction of Liners and Caps for Landfills." *ASTM Standardization News* **19**(1991): 19-21.

ASCE Committee on Construction Equipment and Techniques. "Use of Geotextiles and Geocomposites in the United Kingdom." *Journal of Construction Engineering and Management* **115**(1989): 258-269.

Barbagallo, J. and S. Triano. "High-tech Landfill Caps." *Civil Engineer* **63**(1993):66-68.

Benson, C. and D. Daniel. "Minimum Thickness of Compacted Soil Liners: Analysis and Case Histories." *Journal of Geotechnical Engineering* **120**(1994): 153-172.

Benson, C. and D. Daniel. "Minimum Thickness of Compacted Soil Liners: Stochastic Models." *Journal of Geotechnical Engineering* **120**(1994): 129-152.

Benson, C., H.Zhai, and R. Salwa. "Statistical Sample Size for Construction of Soil Liners." Journal of Geotechnical Engineering **120**(1994): 1704-1724.

Bogardi, I., W. Kelly, and A. Bardossy. "Reliability Model for Soil Liner: Initial Design." *Journal of Geotechnical Engineering* **115**(1990): 658-659.

Bogardi, I., W. Kelly, and A. Bardossy. "Reliability Model for Soil Liner: Postconstruction Design." *Journal of Geotechnical Engineering* **116**(1990): 1811-1830.

Bowles, Joseph E. Physical and Geotechnical Properties of Soils. New York: McGraw-Hill, 1979.

Boynton, S. and D. Daniel. "Hydraulic Conductivity Tests on Compacted Clay." *Journal of Geotechnical Engineering* **111**(1985): 465-478

Callari, James. "Big Business is Getting Wider: Geomembrane Liners." *Plastics World* **51**(14 Feb 1993):14.

Code of Federal Regulation. 40 CFR 241.200, Solid Waste, 1994.

Code of Federal Regulation. 40 CFR 264.300, Hazardous Waste, 1994.

Congressional Quarterly. Federal Regulatory Directory. Washington, D.C.; Congressional Quarterly, Inc., 1994.

Cosler, D. and R. Snow. "Leachate Collection System Performance Analysis." *Journal of Geotechnical Engineering* **110**(1984): 1025-1041.

Daniel, David E. "Predicting Hydraulic Conductivity of Clay Liners." *Journal of Geotechnical Engineering* **110**(1984): 285-300.

Daniel, D. and C. Benson. "Water Content-Density Criteria For Compacted Soil Liners." *Journal of Geotechnical Engineering* **116**(1990): 1811-30.

Das, Braja M. *Advanced Soil Mechanics*. New York: McGraw-Hill, 1983.

Demetracopoulous, A. and L. Sehayek. "Design Considerations for a Novel Landfill Liner." *Journal of Environmental Engineering* **111**(1985):528-539.

Derian, L., K. Gharios, and E. Kavazanjian. "Geosynthetics Conquer the Landfill Law." *Civil Engineer* **63**(1993): 50-53.

El Magahzy, Y., Y. Gowayed, and D. Elton. "Theory of Soil/Geotextile Interaction." *Textile Research Journal* **64**(1994):176-183.

Elsbury, B. and G. Sraders. "Building a Better Landfill Liner." *Civil Engineer* **59**(1989): 57-59.

Empleby, John. Brown-Ferris Industries. Telephone Conversation on 28 September 1995.

Environmental Protection Agency. A Catalog of Hazardous and Solid Waste Publications. Washington, D.C.: Office of Solid Waste, RCRA Information Center, 1990.

Environmental Protection Agency. Criteria for Solid Waste Disposal Facilities: A Guide for Owners/Operators. Washington D.C.; Environmental Protection Agency, March 1993.

Environmental Protection Agency. Environmental Fact Sheet: EPA Releases Final Rules on Liners and Leak Detection Systems. Washington D.C.; Environmental Protection Agency, Jan 1992.

Environmental Protection Agency. EPA's Regulation for Land Disposal of Hazardous Wastes. Washington, D.C.: U.S. Government Printing Office, 1982.

Environmental Protection Agency. Hazardous Waste Management: A Guide to the Regulations. Washington, D.C.: Office of Water and Waste Management, Environmental Protection Agency, 1980.

Environmental Protection Agency. Manual for Ground Water and Leachate Treatment Systems. Cincinnati, Ohio: Office of Research and Development, Environmental Protection Agency, 1995.

Environmental Protection Agency. The Nation's Hazardous Waste Management Program at a Crossroads; The RCRA Implementations Study. Washington, D.C.: Office of Solid Waste and Emergency Response, Environmental Protection Agency, 1990.

Environmental Protection Agency. Safer Disposal for Solid Waste: The Federal Regulations for Landfills. Washington, D.C.; Environmental Protection Agency, Office of Solid Waste and Emergency Response, Jan 1993.

Environmental Protection Agency. RCRA Orientation Manual. Washinton D.C.; Environmental Protection Agency, 1992.

Estornell, P. and D. Daniel. "Hydraulic Conductivity of Three Geosynthetic Clay Liners." *Journal of Geotechnical Engineering* **118**(1992): 1592-1606.

Fuller, Wallace H. Investigation of Landfill Leachate Pollutant Attenuation by Soils. Cincinnati, Ohio; Office of Research and Development, Environmental Protection Agency, 1978.

Gounaris, V., P. Anderson, and T. Holsen. "Characteristics and Enviromental Significance of Colloids in Landfill Leachate." *Environmental Science and Technology* **27**(1993): 1381-1387.

Harrop, Kingsley. "Clay Liner Permeability: Evaluation and Variation."*Journal of Geotecnical Engineering* **111** (1985): 954-949.

Hughs, Larry N., "Exchanging Wastes." *Civil Engineer* **63**(1993): 72-73.

Jackson, D., and D. Bisson. "Comparison of Laboratory Batch Methods and Large Columns for Evaluating Leachate from Molofilled Solid Wastes." *Journal of the Air and Waste Management Association* **40**(1990): 1514-1521.

Koenig, Reinhard W., "Hazardous Waste Landfill Liners." *Term Paper for CE361, Rose-Hulman Institute of Technology*, Nov, 93.

Koerner, R. and D. Daniel. "Better Cover-Ups." *Civil Engineering* **62**(1992): 55-57.

Koerner, R. and J. Welch. *Construction and Geotechnical Engineering Using Synthetic Fabrics*. New York, John Wiley and Sons, Inc, 1980.

Korfiatis, G., and A. Demetracopoulos. "Flow Characteristics of Landfill Leachate Collection Systems and Liners." *Journal of Environmental Engineering* **112** (1986):538-550.

Lafleur, J. and A. Rollin. "Filter Criteria for Geotextiles: Relevance and Use." J*ournal of Geotechnical Engineering* **109**(1983): 1630-1637.

LaGrega, M., P. Buckingham, and J. Evans. *Hazardous Waste Management*. New York; McGraw-Hill, 1994.

Landreth R. and D. Carson. Inspection Techniques for the Fabrication of Geomembrane Field Seams. Cincinnati, Ohio; Risk Reduction Labratory, Environmental Protection Agency, 1991.

Management of World Wastes, The. "EPA Evaluates Lanfill Covers." *The Management of World Wastes* **31**(1988): 8.

McEnroe. Bruce M., "Steady Drainage of Landfill Covers and Bottom Liners." *Journal of Environmental Engineering* **115**(1989): 1114-1122.

McEnroe, B., and P. Schroeder. "Leachate Collection in Landfills: Steady Case." *Journal of Environmental Engineering* **114**(1988): 1052-1061.

Mohammadian, M. N. Allen, and M. Edge."Environmental Degradation of Polyethylene Terephthalate." *Textile Research Journal* **61**(1991): 690-696.

Monteleone, Michael. "Landfill Liner Quality." *Civil Engineer* (1990): 47-49.

Neufeld, R. and S. Wallach. "Chemical and Toxicity Analysis of Leachates From Coal Conversion Solid Wastes." *Journal of the Water Pollution Control Federation* **56**(1984):266-273.

Oweis, I., D. Smith, R. Ellwood, and D. Greene. "Hydralic Characteristics of Municipal Refuse." *Journal of Geotechnical Engineering* **116**(1990):539-553.

PEI Associates, Inc. Operation and Maintenance Manual for Fabric Filters. Research Triangle Park, North Carolina: Office of Research and Development, Environmental Protection Agency, 1986.

Peirce, J., G. Sallfors, and E. Peterson. "Clay Liner Construction and Quality Control." *Journal of Environmental Engineering* **112**(1986): 13-24.

Peyton, L. and R. Schroeder. "Evaluation of Landfill-Liner Design."*Journal of Environmental Engineering* **116**(1990): 421-437.

Richardson, G. and J. Bove. "Geosynthetics: Cleanup Tools." *Civil Engineer* **58**(1988):40-42.

Richardson, G. and E. Kavazanjian. RCRA Subtitle D(258) Seismic Design Guidance for Municipal Solid Waste Landfill Facilities. Washington D.C., Environmental Protection Agency, 1993.

Rollin, A. L. "Filtration Opening Size of Geotextile." *ASTM Standardization News* **14** (1986):50-52.

Sansome, L and R. Koerner. "Fine Fraction Filtration Test to Assess Geotextile Filter Performance." *Geotextiles and Geomembranes* **11**(1992) 371-393.

Science Applications International Corporation and SCS Engineers. Analysis of the Potential Effects of Toxics on Municipal Solid Waste Management Options. Cincinnati, Ohio; Risk Reduction Engineering Laboratory, Environmental Protection Agency, April 1995.

Seed R. and R. Boulanger. "Smooth Shear Strenghts: Compaction Effects. "*Journal of Geotechnical Engineering* **117**(1991): 686-693.

Smiley, Carl H. "Synthetic Liners Increase Siting Options." *The Management of World Wastes* **26**(1983): 15-17.

Stark, T. and A. Poeppel. "Landfill Liner Interface Strength From Torsional-Ring-Shear Tests." *Journal of Geotechnical Engineering* **120**(1994)597-615.

Stessel, R. and P. Goldsmith. "Flexible Membrane Liner Testing in Waste Management." *Journal of the Air and Waste Management Assosication* **42**(1992): 1178-1185.

Suits, David L. "Index Versus Design Properties; Geotextile Permeability and Filtration." *ASTM Standardization News* **14**(1986):46-49.

Suits, David L. "Permeability and Filtration: Performance Versus Index Testing." *ASTM Standardization News* **20**(1992):36-39.

Tannis, Richard. Foam Seal Inc. Conversation with on 8 Sept 1995.

Wagner, R. and G. Yogis. Guide to Environmental Analytical Methods. Schenectady, New York; Genium Publishing Corporation, 1992.

Walsh, P. and P. O'Leary. "Sanitary Landfill Design Procedures." *Waste Age* **22**(1991): 97-98.

Wang, M. and C. Huang. "Soil Compaction and Permeabiliity Prodiction Models." *Journal of Environmental Engineering* **110**(1984): 1063-1083

Waste Age. "1995 Landfill Liner and Geotextile Guide." *Waste Age* **26**(1995): 101-104.

Wyss, A., H. Willard, R. Evans, R. Schmitt, R. Sherman, D. Bruehl, E. Greco. Closure of Hazardous Waste Surface Impoundments. Cincinnati, Ohio: Office of Research and Development, Environmental Protection Agency, 1980.

CITED REFERENCES

1. Kupchela, C., and M. Hyland. *Environmental Science: Living Within the System of Nature*. 3rd Edition, Englewood Cliffs, New Jersey; Prentic Hall, 1993.

2. Indiana Department of Environmental Management. The IDEM Multi-Media Resource Manual. Indianapolis, Indiana.

3. Cadwallader, Mark. "New Regulations Alter Liner Usage." *The Management of World Wastes* **31**(1988): 26.

4. Code of Federal Regulation. 40 CFR 258, Solid Waste Landfills, 1994.

5. Koerner, G., R. Koerner, and J. Martin. "Design of Landfill Leachate-Collection Filters." *Journal of Geotechnical Engineering* **120**(1994): 1792-1803.

6. Koerner, R. and G. Koerner. Landfill Leachate Clogging of Geotextile (and Soil) Filters. Cincinnati, Ohio: Risk Reduction Engineering Laboratory, Environmental Protection Agency, 1991.

7. Desharnais, Brian M. "Analysis of a New Geotextile Design for Stormwater Infiltration Trenches." Graduate Thesis, Rose-Hulman Institute of Technolgy, 1995.

8. Koerner, George M. Geosynthetic Research Institute, Drexel University. Telephone Conversation with Author on 8 Sept 1995.

9. Daniel, David E. University of Texas at Austin. Telephone conversation with author on 8 Sept 1995.

10. Baas, Thomas. Contech Construction. Telephone Conversation on 11 Sept 1995.

11. Goodrum, Richard. Trevira Manufacturers. Telephone Conversation with on 11 Sept 1995.

12. Neese, Terry. Yaw Hill Waste Facility. Telephone Conversation on 3 October 1995.

13. Plater, Z., R. Abrams, and W. Goldfarb. *Environmental Law and Policy; Nature, Law, and Society*. St Paul, Minnesota; West Publishing Company, 1992.

14. Davis, M. and D. Cornwell. *Introduction to Environmental Engineering*. New York: McGraw Hill Inc., 1991.

15. Ichniowski, T. and D. Rubin. "U.S. Issues New Waste Rules." *ENR* **227**(1991):8-9.

16. Al - Salim, Zaidoon. Indiana Department of Environmental Management. Telephone Conversation on 6 September 1995.

17. Ghassemi, Masood. "Leachate Collection Systems." *Journal of Environmental Engineering* **112**(1986): 613-617.

18. Daniel, D. and R. Koerner. "Landfill Liners From Top to Bottom." *Civil Engineer* **61**(1991): 49-50.

19. Institute for Solid Wastes. Municiple Refuse Disposal. Chicago; American Public Works Association, 1970.

20. Lutton, R., G. Regan, and L. Jones. Design and Construction of Covers For Solid Waste Landfills. Cincinnati, Ohio: Solid and Hazardous Waste Research Division, Municiple Environmental Research Laboratory, Environmental Protection Agency, 1979.

21. Chlebowy, Belle. Rumpke and Rumpke, Inc. Telephone Conversation on 19 September 1995.22. Woods, Randy. "Building a Better Liner System." *Waste Age* **23**(1992): 26-28.

22. Woods, Randy. "Building a Better Liner System." *Waste Age* **23**(1992): 26-28.

23. Chian, E. and F. DeWalle. Compilation of Methodology for Measuring Pollution Parameters of Landfill Leachate. Cincinnati, Ohio; Office of Air, Land, and Water Use, Environmental Protection Agency, 1975.

24. Buranek, Dennis., "Construction Guide-Liners." *Civil Engineer* 57(1987):62-64.

25. Demetracopoulous, A., L. Sehayek, and H.Erdogan. "Modeling Leachate Production From Municipal Landfills." *Journal of Environmental Engineering* 112(1986): 849-865.20.

26. Ragle, N., J. Kissel, J. Ongerth, and F. DeWalle. "Composition and Variability of Leachate from Recent and Aged Areas Withing A Municipal Landfill." *Water Environment Research* 67(1995): 238-242.

27. Phaneuf, R.J. "A States Perspective on CQA in Environmental Containment System Design and Construction." Proceedings of the 6th Geotechnical Research Institute Seminar on MQC and CQC of Geosynthetics. Industrial Fabrics Association, 1993.

28. Haxo, H. Jr., R. Haxo, and T. Kellogg. Liner Materials Exposed to Municipal Solid Waste Leachate. Cincinnati, Ohio; Office of Research and Development, Environmental Protection Agency, 1979.

29. Qasim, S. and W. Chiang. Sanitary Landfill Leachate; Generation Control, and Treatment. Lancaster, Pennsylvania; Technomic Publishing Company, Inc., 1994.

30. Koerner, G. and R. Koerner. Biological Activity and Potential Remediation Involving Geotextile Landfill Leachate Filters. Washington D.C.; Environmental Protection Agency, 1992.

31. Robinson, H. and P. Maris. "The Treatment of Leachates From Domestic Waste in Landfill Sites." *Journal of the Water Pollution Control Federation* **57**(1985):30-38.

32. Kelly, Harlan G. "Pilot Testing for Combined Treatment of Leachate From a Domestic Waste Landfill Site." *Journal of the Water Pollution Control Federation* **59**(1987): 254-261.

33. Keenan, J., R. Steiner, and A. Fungaroli. "Landfill Leachate Treatment." *Journal of the Water Pollution Control Federation* **56**(1984): 27-33.

34. Keenan, P., J. Iza, and M. Switzenbaum. "Inorganic Solids Development in a Pilot-Scale Anaerobic Reactor Treating Municipal Solid Waste Landfill Leachate." *Water Environment Research* **65**(1993): 181-188.

35. American Society For Testing and Materials. *Annual Book of ASTM Standards: Construction, Section 4, Volume 04.09.* Philadelphia, Pennsylvania: ASTM, 1994.

36. Koerner, Robert M. *Geosynthetics in Filtration, Drainage and Erosion Control.* New York; Elsevier Applied Science, Inc., 1992.

37. Amoco Fabrics and Fibers Company. *Geotextile Reference Manual.* Atlanta, Georgia: Amoco Fabrics and Fibers Company, 1995.

38. Duncan, Janice M., Amoco Fabrics and Fibers Company. Telephone Conversation on 16 October 1995.

39. Koerner, Robert M. Designing with Geosynthetics. Englewood Cliffs, New Jersey; Elsevier Applied Science, Inc., 1992.

40. Geocomp, Inc., Fact Sheet on GT-80AP, not dated.

41. Matrecon, Ian. Lining of Waste Impoundment and Disposal Facilities. Cincinnati, Ohio: Municipal Environmental Research Laboratory, Office of Research and Development, Environmental Protection Agency, 1980.

42. Koerner, George M. Geosynthetic Research Institute, Drexel University. Telephone Conversation with Author on 8 April 1996.

43. Sawyer, C. and P. McCarty. *Chemistry for Environmental Engineering*. 3rd Edition, New York: McGraw-Hill Company, 1978.

APPENDICES

Appendix A - Biochemical Oxygen Demand

Biochemical Oxygen Demand was tested using the dissolved oxygen meter method in accordance with the *Standard Methods for the Examination of Water and Wastewater.* Testing was performed using a YSI model 54A oxygen meter (RHIT property # CE0056). The procedure is contained in Table A1.

Table A1: Biochemical Oxygen Demand Test Procedure

Step #	Procedure
1	Obtained 5.0 ml sample of leachate and diluted in 1.0 liter of distilled water for leachate #1. Did not dilute leachate #2 for test. Preliminary test revealed that seed was not necessary for the performed test.
2	Placed 10.0 ml of sample in BOD bottle.
3	Checked the pH of the sample to be tested. Without diluting the sample by more than 0.5%, adjusted the pH to between 6.5 and 7.4 using sulfuric acid or sodium hydroxide.
4	Added two dashes of HACH nitrification inhibitor to each BOD bottle.
5	Filled each BOD bottle with the sample up to the ground portion of the neck.
6	Measured and recorded the initial DO and temperature of each bottle with the DO meter.
7	Being careful to avoid trapping air bubbles in the BOD bottles, water seal and stoppered each bottle.
8	Incubated the bottles for 5 days at 20 C.
9	After 5 days, measured and recorded the final DO of each bottle.
10	Taking the difference between the initial dissolved oxygen reading and the dissolved oxygen reading on day 5 as the final BOD_5. Multiplied by 6000 for leachate #1 and 30 for leachate #2.

Table A2: Biochemical Oxygen Demand Test Results, BOD_5 (mg/l),

Unfiltered Leachate

Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean BOD_5
1	25500	23300	24500	22500	21000	23400
2	17700	18900	23700	21700	16800	19800
3	20700	20600	25200	19800	18900	21000
4	221.5	200.5	216.5	191	222.5	210
5	195.5	210	183	175	199	193
6	185	205.5	195.5	198	193.5	196

Table A3: Biochemical Oxygen Demand Test Results, BOD_5 (mg/l),

Trevira 1135

Days	Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean BOD_5
30	1	18900	19200	-	-	-	19050
	2	17600	17900	-	-	-	17750
	3	16900	17400	-	-	-	17150
60	1	19200	16400	-	-	-	17800
	2	14500	15900	-	-	-	15200
	3	18100	17300	-	-	-	17700
90	1	17900	18300	16400	-	-	17500
	2	16700	16700	18900	-	-	17400
	3	14500	15600	17000	-	-	15700
30	4	163	176	237	178	202	191
	5	242	202	204	137	147	186
	6	170	186	163	156	228	181
60	4	192	189	182	239	210	204
	5	176	165	214	164	182	180
	6	192	200	192	160	161	181
90	4	204	231	222	207	189	210
	5	174	193	215	198	203	197
	6	197	128	147	170	176	163

Table A4: Biochemical Oxygen Demand Test Results, BOD_5 (mg/l),

Amoco 2019

Days	Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean BOD_5
30	1	18000	19500	-	-	-	18800
	2	18700	21400	-	-	-	20100
	3	23000	16500	-	-	-	19800
60	1	17300	19200	-	-	-	18300
	2	18900	21000	-	-	-	20000
	3	17400	19500	-	-	-	18500
90	1	22600	21700	19500	-	-	21300
	2	20500	16700	18900	-	-	19700
	3	14400	18900	17400	-	-	16900
30	4	185	233	169	230	184	200
	5	191	216	174	200	207	203
	6	179	150	192	189	152	172
60	4	210	206	189	231	228	213
	5	258	178	230	205	184	211
	6	204	164	148	158	164	168
90	4	216	231	164	237	158	201
	5	218	240	163	207	193	204
	6	227	186	165	170	159	181

Table A5: Biochemical Oxygen Demand Test Results, BOD_5 (mg/l),

Amoco 4508

Days	Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean BOD_5
30	1	19900	17800	-	-	-	18800
	2	18600	17800	-	-	-	18200
	3	17100	18000	-	-	-	17600
60	1	23500	21800	-	-	-	22700
	2	19800	16800	-	-	-	18300
	3	22200	21400	-	-	-	21800
90	1	17800	19900	21100	-	-	19600
	2	23000	21700	15600	-	-	20100
	3	14300	17600	17800	-	-	16600
30	4	225	207	276	251	261	244
	5	243	210	195	198	204	210
	6	147	168	165	128	121	146
60	4	225	222	191	245	228	222
	5	179	211	211	209	198	202
	6	129	123	135	102	116	121
90	4	165	203	234	215	225	208
	5	179	203	210	164	168	185
	6	125	135	110	198	149	143

Table A6: Biochemical Oxygen Demand Test Results, BOD_5 (mg/l),

Amoco 4551

Days	Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean BOD_5
30	1	15600	18000	-	-	-	16800
	2	24000	20100	-	-	-	22100
	3	21300	19800	-	-	-	20600
60	1	17200	16900	-	-	-	17100
	2	18100	19500	-	-	-	18800
	3	14500	13800	-	-	-	14200
90	1	18000	17500	21300	-	-	18900
	2	15300	17900	28400	-	-	20500
	3	26400	20400	21000	-	-	22600
30	4	187	190	237	160	254	206
	5	131	210	293	167	191	198
	6	125	138	102	178	189	146
60	4	195	152	303	226	161	207
	5	175.5	185	215	224	183	196
	6	120	208	165	181	120	159
90	4	146	144	176	183	206	171
	5	218	206	258	158	219	212
	6	209	129	128	185	179	166

Table A7: Biochemical Oxygen Demand Test Results, BOD_5 (mg/l), Geocomposite

Days	Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean BOD_5
30	1	16500	27900	-	-	-	22200
	2	20800	18600	-	-	-	19700
	3	17500	19900	-	-	-	18700
60	1	10900	15600	-	-	-	13300
	2	23400	21200	-	-	-	22300
	3	14500	21900	-	-	-	18200
90	1	17200	19800	19500	-	-	18800
	2	21600	24200	16700	-	-	20800
	3	13500	19800	17900	-	-	17100
30	4	170	182	214	207	183	191
	5	200	243	215	207	180	209
	6	190	125	193	154	136	159
60	4	156	153	149	156	167	156
	5	204	209	180	189	189	195
	6	126	128	148	120	163	137
90	4	158	150	227	163	201	180
	5	219	182	174	198	167	188
	6	201	121	144	116	173	151

Appendix B - Chemical Oxygen Demand

Testing was performed using the reflux method in accordance with the *Standard Methods for the Examination of Water and Wastewater*. The procedure is contained in Table B1.

Table B1: Chemical Oxygen Demand Procedure

Step #	Procedure
1	Cleaned COD Bottle and Diluted high concentration Leachate: 1:250.
2	Placed 10.0 ml of sample in COD refluxing flask.
3	Added 5 ml $K_2Cr_2O_7$ Potassium Dichromate.
4	Added 15 ml of H_2SO_4 Sulfuric Acid with Ag_2SO_4, Added Boiling Chips.
5	Cooled while mixing to avoid possible loss of volatile materials.
6	Added 0.2 g of $HgSO_4$ Mucuric Acid.
7	Attached the flask to the condenser and started heating.
8	Boiled Sample for approximately 2 hours.
9	Turn off heat and let sit until sample stopped boiling.
10	Let sample cool to room temperature.
11	Used distilled water to dilute the sample to approximately 70 ml.
12	Cooled sample again to room temperature.
13	Titillated the excess dichromate with standard ferrous ammonium sulfate ($Fe(NH_2)_2(SO_4)_2*6H_20$), using a derroin indicator. Used 2 or 3 drops.
14	Took as the endpoint the sharp color change from blue-green to reddish brown.
15	Refluxed in the same manner a blank consisting of distilled water in the same volume as the sample with the reagents. Determined Normality of Titrant.
16	COD (mg/l) = ((Blank Titrant Vol - Sample Titrant Vol)*Normality of the Titrant*8000 / Volume of Sample) * Dilution Factor.

Table B2: Chemical Oxygen Demand Test Results (mg/L)

Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean COD
1	45816	41832	47808	41832	39840	43426
2	46920	34680	34680	32640	40800	37944
3	47232	33456	37392	35424	41328	38966
4	339	368	310	358	348	345
5	437	428	464	464	410	435
6	310	426	450	364	380	386

Table B3: Chemical Oxygen Demand Test Results (mg/l)

Trevira 1135

Days	Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean COD
30	1	35856	37848	33864	31872	27888	33466
	2	32640	20400	26520	18360	22440	24072
	3	33456	29520	31488	25584	19680	27946
60	1	25896	29880	23904	25896	27888	26693
	2	28560	24480	26520	28560	22440	26112
	3	25584	27552	35424	31488	29520	29914
90	1	27888	27888	29880	23904	25896	27091
	2	30600	32640	30600	22440	18360	26928
	3	29520	31488	25584	33456	23616	28733
30	4	300	339	310	290	310	310
	5	310	347	383	419	356	363
	6	333	233	302	395	341	321
60	4	348	281	348	319	329	325
	5	437	293	419	293	329	354
	6	201	419	248	310	349	305
90	4	339	184	174	387	290	275
	5	383	320	392	374	365	367
	6	233	349	372	256	295	300

Table B4: Chemical Oxygen Demand Test Results (mg/l)

Amoco 2019

Days	Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean COD
30	1	19920	25896	37848	25896	17928	25498
	2	22440	18360	18360	26520	30600	23256
	3	29520	27552	23616	19680	27552	25584
60	1	31872	29880	17928	15936	23904	23904
	2	22440	22440	20400	24480	22440	22440
	3	33456	27552	23616	27552	25584	27552
90	1	27888	17928	25896	19920	25896	23506
	2	26520	24480	22440	32640	30600	27336
	3	33456	21648	17712	29520	33456	27158
30	4	397	310	339	416	319	356
	5	329	455	464	356	383	397
	6	116	333	372	201	256	256
60	4	300	368	203	368	290	306
	5	364	400	374	392	383	383
	6	349	264	372	388	357	346
90	4	411	194	358	290	300	311
	5	410	419	455	401	410	419
	6	318	326	310	217	295	293

Table B5: Chemical Oxygen Demand Test Results (mg/l)

Amoco 4058

Days	Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean COD
30	1	19920	37848	19920	21912	433824	28685
	2	22440	22440	26520	28560	24480	24888
	3	29520	23616	19680	32472	27552	26568
60	1	23904	35856	25896	21912	23904	26294
	2	20400	22440	28560	20400	28560	24072
	3	23616	31488	27552	29520	19680	26371
90	1	27888	23904	31872	29880	21912	27091
	2	24480	22440	20400	26520	28560	24480
	3	27552	29520	33456	19680	25584	27158
30	4	310	348	368	319	339	337
	5	428	338	329	401	392	377
	6	171	364	318	233	264	270
60	4	378	286	387	252	319	324
	5	401	428	437	392	410	413
	6	217	341	287	349	279	295
90	4	290	358	368	339	319	335
	5	360	301	382	320	329	339
	6	326	310	403	318	279	327

Table B6: Chemical Oxygen Demand Test Results (mg/l)

Amoco 4551

Days	Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean COD
30	1	27888	31872	29880	21912	23904	27091
	2	28560	27540	33660	20400	16320	25296
	3	33456	32472	19680	34440	21648	28339
60	1	21912	21912	23904	35856	29880	26693
	2	26520	30600	22440	26520	28560	26928
	3	29520	17712	37392	27552	33456	2912
90	1	31872	29880	23904	31872	19920	27490
	2	16320	20400	26520	38760	24480	25296
	3	23616	29520	23616	27552	31488	27158
30	4	348	348	281	339	319	327
	5	338	437	410	455	419	412
	6	302	357	333	233	310	307
60	4	368	232	310	261	319	298
	5	419	437	428	319	383	397
	6	225	333	225	341	295	284
90	4	348	300	319	348	329	329
	5	347	491	446	428	409	424
	6	217	209	295	264	310	259

Table B7: Chemical Oxygen Demand Test Results (mg/l)

Geocomposite

Days	Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean COD
30	1	23904	27888	25896	25896	27888	26294
	2	30600	22440	28560	30600	28560	28152
	3	25584	23616	33456	31488	29520	28733
60	1	29880	25896	33864	37848	27888	31075
	2	28560	20400	18360	22440	28560	23664
	3	29520	33456	17712	27552	29520	27552
90	1	21912	39840	23904	37848	19920	28685
	2	18360	22440	34680	14280	36720	25296
	3	29520	43296	45264	17712	33456	33850
30	4	387	378	378	339	329	362
	5	383	464	437	383	419	417
	6	419	302	372	302	349	349
60	4	339	310	349	310	319	325
	5	383	329	275	374	401	352
	6	240	372	357	295	349	322
90	4	242	348	3489	281	319	308
	5	310	292	383	410	419	363
	6	271	364	302	264	256	291

Appendix C - Total Suspended Solids

Testing was performed using the total nonfiltrable residue dried at 103-105 C method in accordance with *Standard Methods for the Examination of Water and Wastewater*. The procedure is contained in Table C1.

Table C1: Suspended Solids Testing Procedure

Step #	Procedure
1	Using sterile forceps, placed a sterile glass fiber filter over porous plate of receptacle of membrane filter apparatus.
2	Placed matched funnel unit over receptacle and locked it in place.
3	Under vacuum, washed the filter with three successive 20 ml washings of distilled water.
4	Removed rinsed filter from membrane filter apparatus and placed in a tin weighing dish.
5	Dried in an oven at 103 to 105 C for at least 2 hours.
6	Cooled in desiccator to room temperature.
7	Weighed before use.
8	Replaced the glass fiber filter over porous plate of receptacle of membrane filter apparatus.
9	Placed matched funnel unit over receptacle and lock it in place.
10	Under a vacuum, filtered 5.0 ml sample for test 1,2, and 3, and 50.0 ml sample for test 4,5, and 6.
11	Removed glass fiber filter from membrane filter apparatus and placed in a tin weighing dish.
12	Dried in an oven at 103 to 105 C for at least 2 hours.
13	Cooled in desiccator to room temperature.
14	Weigh the sample.
15	Weight of suspended solid ((step 14 - step 7)*1000)
16	Total suspended solid (step 15 / (step 10 / 1000)) in mg/l.

Table C2: Total Suspended Solids (mg/l), Unfiltered Leachate

Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean TSS (mg/l)
1	41800	35100	31500	42100	38400	37800
2	30900	48300	31700	37400	40400	37700
3	29200	24000	32900	27600	24200	27600
4	199	208	212	201	269	218
5	212	232	185	256	231	223
6	250	233	258	233	184	232

Table C3: Total Suspended Solids (mg/l), Trevira 1135

Days	Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean TSS (mg/l)
30	1	11900	14000	16700	13800	13900	14000
	2	10200	10100	7700	8800	10200	9400
	3	15800	16500	15300	16600	16800	16000
60	1	3000	3000	3100	2900	3600	3100
	2	3000	3100	3200	3200	2600	3000
	3	2800	2500	3000	2600	2400	2700
90	1	220	190	240	210	170	210
	2	280	220	100	180	100	180
	3	125	130	150	135	140	140
30	4	95	105	82	92	99	95
	5	120	107	106	101	128	113
	6	142	108	146	136	136	136
60	4	82	79	98	78	100	88
	5	173	143	112	138	95	132
	6	154	168	161	151	164	160
90	4	111	121	98	131	118	116
	5	123	98	118	121	84	109
	6	103	130	108	135	148	125

Table C4: Total Suspended Solids (mg/l)

Amoco 2019

Days	Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean TSS (mg/l)
30	1	20000	20700	19800	20400	22500	20700
	2	24000	22300	17800	21400	22500	21600
	3	26100	24900	26100	25600	18800	24300
60	1	1250	1600	1560	1420	1390	1400
	2	650	670	720	450	690	640
	3	510	460	350	390	280	400
90	1	120	320	220	170	190	204
	2	160	240	260	40	60	152
	3	10	540	170	190	180	218
30	4	144	146	154	130	175	150
	5	173	264	239	229	200	221
	6	151	152	160	129	133	143
60	4	117	142	146	119	149	135
	5	189	179	179	192	193	186
	6	169	135	131	170	133	148
90	4	103	137	111	127	134	122
	5	199	140	121	206	135	160
	6	191	164	178	186	186	181

Table C5: Total Suspended Solids (mg/l)

Amoco 4508

Days	Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean TSS (mg/l)
30	1	12800	21200	15300	18400	12400	16000
	2	18000	17100	16900	17800	18500	17700
	3	13200	16500	14300	14200	14300	14500
60	1	540	510	650	700	610	740
	2	180	260	100	280	320	230
	3	880	1040	1000	1150	1230	1060
90	1	390	240	230	190	280	266
	2	150	280	290	260	190	234
	3	220	260	240	230	210	232
30	4	143	156	73	140	107	124
	5	67	87	83	84	82	81
	6	98	98	112	90	112	102
60	4	126	113	153	103	95	118
	5	117	109	151	72	112	112
	6	192	182	214	176	194	192
90	4	116	127	132	125	99	120
	5	91	76	86	89	84	85
	6	130	107	123	130	150	128

Table C6: Total Suspended Solids (mg/l)

Amoco 4551

Days	Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean TSS (mg/l)
30	1	15400	14700	13300	14600	12600	14100
	2	15100	13500	14200	14900	14500	14400
	3	14400	15500	17500	15800	15400	15700
60	1	460	490	360	490	420	444
	2	280	400	400	360	320	352
	3	380	460	390	470	410	422
90	1	120	230	95	165	80	138
	2	260	190	260	80	100	178
	3	30	240	10	15	10	61
30	4	68	106	78	63	75	78
	5	80	73	80	89	114	87
	6	53	98	124	129	100	101
60	4	77	97	112	97	84	93
	5	155	126	141	124	144	138
	6	178	123	173	177	175	165
90	4	99	90	107	125	139	112
	5	70	103	73	96.5	68	82
	6	105	159	145	143	156	142

Table C7: Total Suspended Solids (mg/l)

Geocomposite

Days	Test	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean TSS (mg/l)
30	1	19100	17800	19200	14600	14000	16900
	2	10000	10500	10200	10900	11700	10700
	3	14500	14000	16100	16700	15800	15400
60	1	16400	16100	16200	15100	13700	15500
	2	14500	15600	13900	14300	15100	14680
	3	14300	14100	13800	15300	14700	14400
90	1	220	190	240	205	175	206
	2	80	320	380	300	330	282
	3	350	230	660	440	720	480
30	4	136	101	118	113	117	117
	5	92	66	73	119	99	90
	6	107	125	114	77	87	102
60	4	137	134	106	135	93	121
	5	125	110	116	137	165	131
	6	113	130	141	153	150	137
90	4	103	106	85	110	97	100
	5	106	71	91	93	145	101
	6	148	182	157	170	158	163

Appendix D - Metal Concentration

Metal testing for Zinc and Iron was conducted using a Flame Atomic Absorption Spectrophotometry Test by the use of a direct aspiration into an Air-acetylene Method in accordance with *Standard Methods for the Examination of Water and Wastewater.* The procedure is contained in Table D1. The tests were performed using the PYE UNICAM SP9 Atomic Absorption Spectrophotometer (RHIT property # CE 0319).

Table D1: Testing Procedure for Zinc and Iron

Step #	Procedure
1	Obtained 50 ml sample of each leachate and placed in a beaker.
2	Turned on the Atomic Absorption Spectrophotometer. Turned on air flow to 30 psi and acetylene to 12 psi. Ignited the flame.
3	Turned on cathode lamps for both zinc and iron and set to 10 amps. Let warm up approximately 15 minutes.
4	Set wavelength to 248.9 for iron and 213.8 for zinc.
5	Fine tuned the wavelength, fuel/air flow, and bandwidth for each element to give maximum sensitivity.
6	Zeroed the instrument by atomizing deionized distilled water acidified with 1.5 ml concentrated HNO_3/L.
7	Atomized three premade standards for each test so that a calibration curve could be created. Conducted this step five times and used the mean absorbance for the calibration curve. Did not aspirate more than three samples without rezeroing.
8	Atomized the samples to be tested and recorded the absorbance. Conducted this step five times and used the mean absorbance when entering the calibration curve.
9	Using the calibration curve, found the sample's concentration.

Table D2: Unfiltered Leachate Iron Concentration (mg/L)

Test 1	Test 2	Test 3	Average High Concentration
1190	1205	1100	1165
Test 4	Test 5	Test 6	Average Low Concentration
11.0	18.2	11.9	13.7

Table D3: Filtered Leachate Iron Concentration (mg/L)

Trevira 1135

Days	Test 1	Test 2	Test 3	Average High Concentration
30	1175	827	910	971
60	940	901	840	894
90	925	947	730	867
	Test 4	Test 5	Test 6	Average Low Concentration
30	8.8	12.3	8.2	9.8
60	7.3	10.3	8.7	8.8
90	5.7	11.1	7.6	8.1

Table D4: Filtered Leachate Iron Concentration (mg/L)

Amoco 2019

Days	Test 1	Test 2	Test 3	Average High Concentration
30	1170	967	955	1030
60	720	650	715	695
90	780	668	730	726
	Test 4	Test 5	Test 6	Average Low Concentration
30	11.8	15.1	10.7	12.5
60	9.8	13.1	9.8	10.9
90	10.3	13.6	10.5	11.5

Table D5: Filtered Leachate Iron Concentration (mg/L)

Amoco 4058

Days	Test 1	Test 2	Test 3	Average High Concentration
30	1165	1057	1100	1107
60	955	695	610	753
90	620	680	710	670
	Test 4	Test 5	Test 6	Average Low Concentration
30	10.3	9.7	9.2	9.7
60	8.8	9.8	11.5	10.0
90	8.3	9.8	8.4	8.8

Table D6: Filtered Leachate Iron Concentration (mg/L)

Amoco 4551

Days	Test 1	Test 2	Test 3	Average High Concentration
30	1160	864	1050	1025
60	755	655	650	687
90	590	730	570	630
	Test 4	Test 5	Test 6	Average Low Concentration
30	8.0	11.6	10.8	10.1
60	8.0	11.3	10.8	10.0
90	8.8	10.4	9.3	9.5

Table D7: Filtered Leachate Iron Concentration (mg/L)

Geocomposite

Days	Test 1	Test 2	Test 3	Average High Concentration
30	1190	1028	1090	1102
60	720	955	1070	915
90	650	1040	885	858
	Test 4	Test 5	Test 6	Average Low Concentration
30	6.5	8.6	8.5	7.9
60	7.07.3	8.7	8.5	8.0
90	6.5	9.3	11.1	9.0

Table D8: Unfiltered Leachate Zinc Concentration (mg/L)

Test 1	Test 2	Test 3	Average High Concentration
101	102	103	102
Test 4	Test 5	Test 6	Average Low Concentration
0.265	0.240	0.120	0.208

Table D9: Filtered Leachate Zinc Concentration (mg/L)

Trevira 1135

Days	Test 1	Test 2	Test 3	Average High Concentration
30	91	74	86	84
60	98	59	70	75
90	72	73	75	73
	Test 4	Test 5	Test 6	Average Low Concentration
30	0.178	0.060	0.052	0.097
60	0.158	0.001	0.035	0.065
90	0.185	0.002	0.060	0.082

Table D10: Filtered Leachate Zinc Concentration (mg/L)

Amoco 2019

Days	Test 1	Test 2	Test 3	Average High Concentration
30	100	68	89	86
60	79	56	61	65
90	88	64	83	78
	Test 4	Test 5	Test 6	Average Low Concentration
30	0.135	0.130	0.104	0.123
60	0.130	0.130	0.115	0.125
90	0.109	0.111	0.107	0.109

Table D11: Filtered Leachate Zinc Concentration (mg/L)

Amoco 4058

Days	Test 1	Test 2	Test 3	Average High Concentration
30	97	88	93	92
60	94	47	81	74
90	94	76	87	86
	Test 4	Test 5	Test 6	Average Low Concentration
30	0.155	0.007	0.056	0.073
60	0.162	0.016	0.072	0.083
90	0.198	.0155	0.056	0.089

Table D12: Filtered Leachate Zinc Concentration (mg/L)

Amoco 4551

Days	Test 1	Test 2	Test 3	Average High Concentration
30	96	49	91	79
60	64	37	90	63
90	75	44	91	70
	Test 4	Test 5	Test 6	Average Low Concentration
30	0.163	0.055	0.055	0.091
60	0.149	0.060	0.053	0.087
90	0.153	0.070	0.065	0.096

Table D13: Filtered Leachate Zinc Concentration (mg/L)

Geocomposite

Days	Test 1	Test 2	Test 3	Average High Concentration
30	97	88	89	91
60	75	36	85	65
90	78	89	81	83
	Test 4	Test 5	Test 6	Average Low Concentration
30	0.178	0.020	0.072	0.090
60	0.221	0.072	0.023	0.105
90	0.168	0.070	0.054	0.097

Appendix E - Permittivity Results

Table E1: Permittivity Results for

Trevira 1135

Days	Test	h_o (cm)	h_f (cm)	Mean ΔT (sec)	Permittivity (1/sec)
0	1	10.6	1.8	1.68	1.75
	2	10.6	1.8	2.00	1.47
	3	10.6	1.8	1.72	1.71
30	1	28.6	26.5	8064	1.57×10^{-5}
	2	28.6	26.3	9670	1.44×10^{-5}
	3	28.6	27.0	5040	1.90×10^{-5}
60	1	28.6	27.45	8064	8.45×10^{-6}
	2	28.6	26.85	10800	9.71×10^{-6}
	3	28.6	27.2	9240	9.02×10^{-6}
90	1	28.6	27.2	13100	6.36×10^{-6}
	2	28.6	27.1	14940	5.99×10^{-6}
	3	28.6	27.15	13860	6.19×10^{-6}
0	4	10.6	1.8	1.76	1.67
	5	10.6	1.8	1.74	1.69
	6	10.6	1.8	1.78	1.65
30	4	10.6	1.8	1.78	1.65
	5	10.6	1.8	1.96	1.50
	6	10.6	1.8	2.00	1.47
60	4	10.6	1.8	1.80	1.64
	5	10.6	1.8	2.04	1.44
	6	10.6	1.8	2.14	1.38
90	4	10.6	1.8	1.82	1.62
	5	10.6	1.8	2.02	1.46
	6	10.6	1.8	2.44	1.21

Table E2: Permittivity Results for

Amoco 2019

Days	Test	h_o (cm)	h_f (cm)	Mean ΔT (sec)	Permittivity (1/sec)
0	1	10.6	1.8	35.98	0.082
	2	10.6	1.8	49.58	0.059
	3	10.6	1.8	73.10	0.040
30	1	28.9	27.6	10080	7.58×10^{-6}
	2	28.9	27.5	10020	8.23×10^{-6}
	3	28.9	27.4	5040	1.76×10^{-5}
60	1	28.9	28.0	8064	6.51×10^{-6}
	2	28.9	28.1	10860	4.29×10^{-6}
	3	28.9	27.8	9300	6.93×10^{-6}
90	1	28.9	27.8	13100	4.92×10^{-6}
	2	28.9	27.6	15120	5.05×10^{-6}
	3	28.9	28.0	13920	3.77×10^{-6}
0	4	10.6	1.8	47.76	0.0616
	5	10.6	1.8	68.54	0.0429
	6	10.6	1.8	72.82	0.0404
30	4	10.6	1.8	58.32	0.0504
	5	10.6	1.8	161.5	0.0182
	6	28.9	26.7	25.52	0.00515
60	4	10.6	1.8	167.04	0.0176
	5	28.9	26.7	12.28	0.0107
	6	28.9	26.7	55.76	0.0024
90	4	28.9	26.7	15.98	0.0082
	5	28.9	26.7	46.84	0.0028
	6	28.9	26.7	61.52	0.0022

Table E3: Permittivity Results for

Amoco 4058

Days	Test	h_o (cm)	h_f (cm)	Mean ΔT (sec)	Permittivity (1/sec)
0	1	10.3	1.8	2.42	1.20
	2	10.3	1.8	2.50	1.16
	3	10.3	1.8	2.52	1.15
30	1	29.1	27.0	5860	2.12×10^{-5}
	2	29.0	24.5	10100	2.77×10^{-5}
	3	29.1	27.6	5160	1.70×10^{-5}
60	1	29.1	27.7	9560	8.56×10^{-6}
	2	29.1	27.8	10980	6.91×10^{-6}
	3	29.1	27.7	9360	8.74×10^{-6}
90	1	29.1	27.5	14750	6.36×10^{-6}
	2	29.1	27.15	15180	7.58×10^{-6}
	3	29.1	27.8	13980	5.43×10^{-6}
0	4	10.3	1.8	1.98	1.46
	5	10.3	1.8	2.68	1.08
	6	10.3	1.8	2.60	1.11
30	4	10.3	1.8	4.38	0.66
	5	10.3	1.8	3.02	0.96
	6	10.3	1.8	17.8	0.16
60	4	10.3	1.8	5.96	0.49
	5	10.3	1.8	3.32	0.87
	6	10.3	1.8	18.76	0.15
90	4	10.3	1.8	6.46	0.45
	5	10.3	1.8	3.78	0.77
	6	10.3	1.8	31.28	0.093

Table E4: Permittivity Results for

Amoco 4551

Days	Test	h_o (cm)	h_f (cm)	Mean ΔT (sec)	Permittivity (1/sec)
0	1	10.7	1.8	2.04	1.45
	2	10.7	1.8	1.86	1.59
	3	10.7	1.8	1.86	1.59
30	1	28.6	28.4	3600	3.24×10^{-6}
	2	29.0	27.6	10320	7.96×10^{-6}
	3	28.6	20.4	5220	1.07×10^{-4}
60	1	28.6	27.3	8200	9.42×10^{-6}
	2	28.6	27.2	11000	7.57×10^{-6}
	3	28.6	26.8	9420	1.15×10^{-5}
90	1	28.6	27.2	13100	6.36×10^{-6}
	2	28.6	27.1	15300	5.84×10^{-6}
	3	28.6	27.1	14020	6.38×10^{-6}
0	4	10.7	1.8	1.98	1.49
	5	10.7	1.8	1.90	1.56
	6	10.7	1.8	2.26	1.31
30	4	10.7	1.8	3.76	0.788
	5	10.7	1.8	1.96	1.51
	6	10.7	1.8	10.62	0.279
60	4	10.7	1.8	4.32	0.685
	5	10.7	1.8	2.12	1.39
	6	10.7	1.8	16.34	0.181
90	4	10.7	1.8	4.42	0.669
	5	10.7	1.8	2.34	1.26
	6	10.7	1.8	19.04	0.155

Table E5: Permittivity Results for Geocomposite

Days	Test	h_o (cm)	h_f (cm)	Mean ΔT (sec)	Permittivity (1/sec)
0	1	10.5	1.8	1.86	1.57
	2	10.5	1.8	2.08	1.41
	3	10.5	1.8	1.84	1.59
30	1	28.65	26.8	111.26	9.96×10^{-4}
	2	28.65	25.45	10440	1.88×10^{-5}
	3	10.5	1.8	22.8	0.128
60	1	28.65	26.95	8200	1.24×10^{-5}
	2	28.65	26.95	11500	8.83×10^{-6}
	3	28.65	26.8	9420	1.18×10^{-5}
90	1	28.65	27.2	13100	6.58×10^{-6}
	2	28.65	26.95	15360	6.61×10^{-6}
	3	28.65	27.05	14080	6.77×10^{-6}
0	4	10.5	1.8	2.20	1.33
	5	10.5	1.8	2.52	1.16
	6	10.5	1.8	2.38	1.23
30	4	10.5	1.8	2.32	1.26
	5	10.5	1.8	2.74	1.07
	6	10.5	1.8	2.86	1.02
60	4	10.5	1.8	2.62	1.12
	5	10.5	1.8	3.02	0.969
	6	10.5	1.8	3.34	0.876
90	4	10.5	1.8	3.58	0.818
	5	10.5	1.8	3.36	0.871
	6	10.5	1.8	3.86	0.758

Appendix F - Filter Cake Analysis Results

Table F1: COD (mg/l) Results for Amoco 4551

Sample	Unfiltered	30 Days	60 Days	90 Days
1	42720	30260	33820	28480
2	32040	46280	32040	44500
3	40940	40940	23140	33820
4	33820	37380	40940	42720
5	46280	32040	40940	30260
Mean	39160	37380	34176	35956

Table F1: Iron (mg/l) Results for Amoco 4551

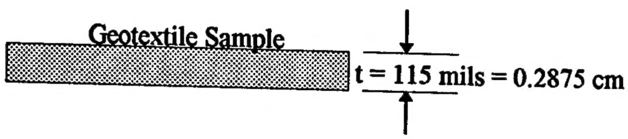
Sample	Unfiltered	30 Days	60 Days	90 Days
1	1280	1050	1150	1100
2	1200	1220	1140	1070
3	1160	1090	1100	1120
4	1240	1120	1180	1090
5	1200	1150	1050	1170
Mean	1216	1126	1124	1110

Appendix G - Example Conversion From Permittivity to Permeability

$$k = \psi * t$$

Where: k = coefficient of permeability (cm/sec)
t = tickness of the sample (cm)
ψ = permittivity (sec^{-1})

<u>Example</u>:



$$\psi = \text{permittivity} = 2.5(sec^{-1})$$

$$\Rightarrow k = 2.5\ (sec^{-1}) * 0.2875\ cm$$

$$= \underline{0.72\ cm/sec}$$